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Probability of Criticality for MOX SNF

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1. PURPOSE

The purpose of this calculation is to provide a conservative (upper bound) estimate of the probability of criticality for mixed oxide (MOX) spent nuclear fuel (SNF) of the Westinghouse pressurized water reactor (PWR) design that has been proposed for use with the Plutonium Disposition Program (Ref. 1, p. 2). This calculation uses a Monte Carlo technique similar to that used for ordinary commercial SNF (Ref. 2, Sections 2 and 5.2). Several scenarios, covering a range of parameters, are evaluated for criticality. Parameters specifying the loss of fission products and iron oxide from the waste package are particularly important. This calculation is associated with disposal of MOX SNF.

This calculation is associated with disposal criticality analysis and has been prepared in accordance with procedure AP-3.12Q (Rev. 0, ICN 0, effective 06/30/1999).

2. METHOD

A Monte Carlo technique with conservative probability distributions of the degradation parameters is used to convert a large set (240) of deterministic calculations of k_{eff} for a waste package (based on values of degradation parameters covering the entire possible range) into a probability that k_{eff} exceeds the criticality limit (CL). The CL used for this calculation is 0.92 (Assumption 3.10).

The likely internal degradation scenario for this is a variation of the standard scenario, which is shown in six stages (A through D) in Figure 2-1. Stage A (Figure 2-1A) is the intact configuration, which is assumed to exist just before breach of the waste package irrespective of the time to breach (Assumption 3.1). The water breaching the waste package will fill the waste package to the level of the breach. For several hundred years following the filling of the waste package, the dominant degradation process will be the corrosion of the carbon steel and aluminum components. The first structural components to fail will be the side guides and corner guides, which are composed of carbon steel (Figure 2-1B). Following those failures, the rest of the structural material and thermal shunts will fail, leading to the fully collapsed basket configuration (Figure 2-1C). Stages A through D carry the scenario from the intact configuration through corrosion of the carbon steel and borated stainless steel and loss of boron from the waste package.

This calculation evaluates the effect of the degradation beyond Stage D, which is characterized by the collapse of the assembly spacer grids, leading to Stage E, and the loss of cladding, leading to Stage F. In reality, these two processes may take place simultaneously. Since the zircaloy spacer grids (Ref. 3, Table 4.2-1) are generally thinner than the zircaloy fuel pin cladding (Ref. 4, p. 26), and since the spacer grids are exposed to corrosion from both sides while the cladding is only exposed to corrosion from one side, the assemblies are more likely to collapse (Figure 2-1E) before significant degradation of the fuel matrix itself (Figure 2-1F). However, the Monte Carlo simulation does consider the possibility of these processes occurring simultaneously, with appropriate probability weighting, to ensure that the result represents a conservative estimate.

The degradation scenario illustrated in Figure 2-1 has been used as the basis for earlier estimates of criticality probability for the commercial SNF waste package (Ref. 5, Section 2 and Ref. 6, Section 2), and it is consistent with the degradation analysis methodology established in Reference 7 (pp. 3-11 through 3-13).

The Monte Carlo technique is implemented by a software routine, "montecarlomox.c" that builds the expected criticality statistics. These statistics are based on the two batches of MOX fuel that have significant criticality potential: (a) 304 assemblies with initial 4 wt% ^{239}Pu loading (pseudo enrichment) and 35.6 GWd/MTHM burnup and (b) 76 assemblies with initial 4.5 wt% ^{239}Pu loading and 39.4 GWd/MTHM burnup. It should be noted that some criticality evaluation results for the 4% Pu with 50.1 GWd/MTHM burnup are presented in Reference 1 (pp. 3 and 38 through 42 and Figures 6.3.3.2-4 and 6.3.3.2-3). However, that document shows that when this higher burnup fuel is placed in the 12 PWR waste package (which is required for temperature control), it has a k_{eff} that is at least 0.13 lower than the two more critical batches (4.5 wt%, 39.4

GWd/MTHM and 4.0 wt%, 35.6 GWd/MTHM). This fact can be seen by comparing Figures 6.3.3.2-3 and 6.3.3.2-1 in Reference 1 (pp. 39, 41). Since none of the k_{eff} values used for this calculation is greater than 0.95 (as can be seen from the listing of the two tables in Attachment V), a downward displacement by 0.13 would take the 4% Pu 50.1 GWd/MTHM assemblies completely out of consideration for criticality. The remaining assemblies have been shown to be non-critical (Ref. 1, p. 3). Each batch is subjected to 30,000 Monte Carlo realizations. Each Monte Carlo realization begins with a random selection of whether the waste package is dripped on and whether the waste package is breached on the top before it is breached on the bottom. For realizations that satisfy both conditions, the time before breach and the time between first top breach and first bottom breach (duration of waste package "bathtub" configuration) are randomly generated. Also generated at this time are the parameters for the distribution of rates of assembly collapse and fission product loss (which results from the degradation of the fuel matrix).

For each time step of the numerical integration of a Monte Carlo realization the degree of assembly collapse and the quantity of fission products lost from the fuel matrix are also calculated or generated randomly from specified probability distributions. The k_{eff} of the resulting configuration is then calculated by interpolating between table entries.

If the calculated k_{eff} is less than the CL, then the algorithm proceeds to the next time step and the process repeats. If the calculated k_{eff} exceeds the CL, the realization ends and the time of criticality is sorted into discrete increments or bins 1,000 years wide for later processing. In practice this is accomplished by incrementing the number of criticality counts by the number of assemblies in the batch (304 or 76) for the appropriate time-step bin. Once the criticality is recorded the simulation moves to the next realization, and the process is repeated until the 30,000 realizations have generated for the first batch of assemblies, after which the process repeats with the second batch of assemblies. After all the batches have been processed, the summary statistics of the resulting probability distribution are generated. The principal statistics are the frequency of criticality, the cumulative probability of criticality, and the expected number of criticalities, all as a function of time up to 100,000 years in discrete time steps of 1,000 years.

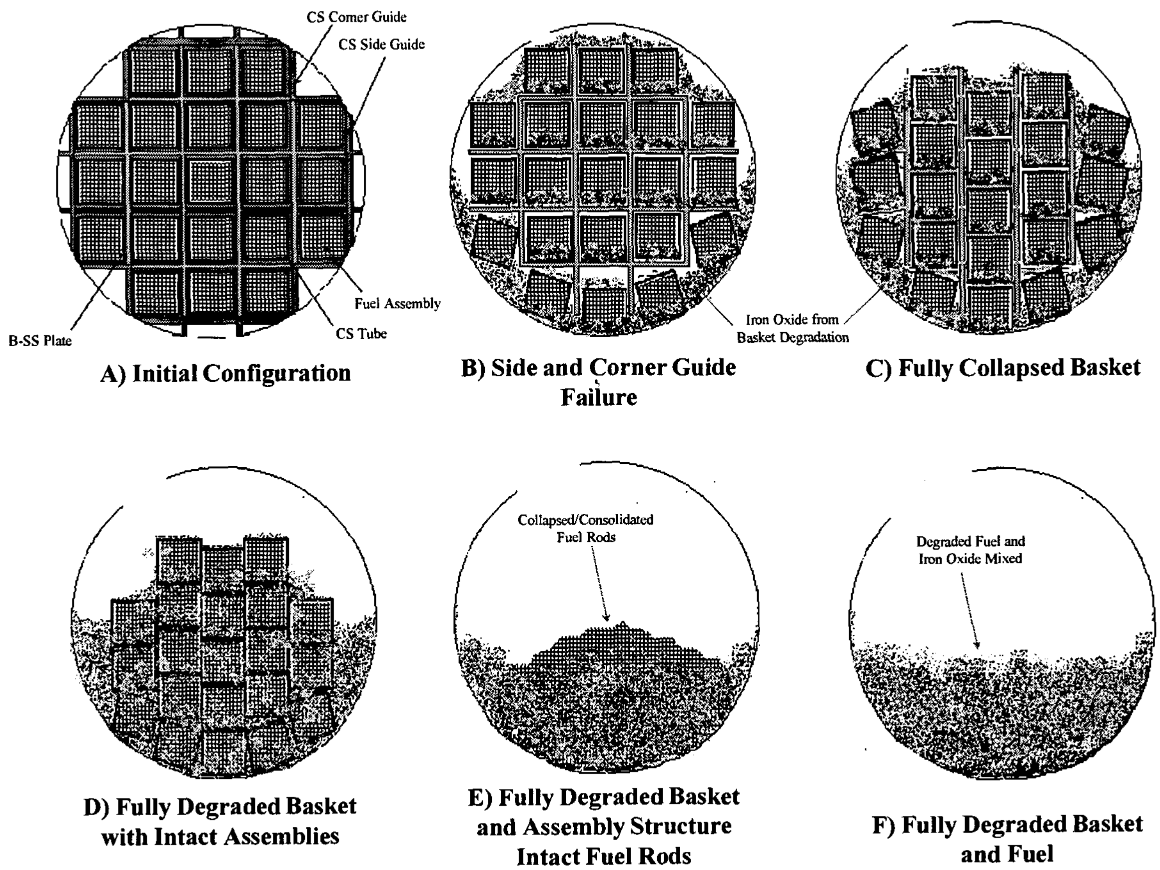

Figure 2-1. Degradation Sequence for the 21 PWR Absorber Plate Waste Package

3. ASSUMPTIONS

3.1 It is assumed that the spent fuel and other internal components of the waste package do not degrade before the breach of the waste package. The basis for this assumption is that the dry interior of the waste package is to be rendered inert with helium before sealing (Ref. 8, p. 4-23), so there are no agents for chemical reaction. This assumption is used throughout Section 5 and is mentioned in Section 2.

3.2 It is assumed that at the simulated time of the beginning of the Monte Carlo calculation, the carbon steel, borated stainless steel, and aluminum components of the basket have completely degraded and all of the boron has leached from the waste package. The bases for this assumption are the observations that (a) no criticality will occur before the basket completely degrades (Ref. 9, Tables 6.1-1 and 6.1-6), so there is no point accounting for those earlier degradation processes and (b) it is conservative to assume that no boron is present to act as a neutron absorber. This assumption is used throughout Section 5.

3.3 The MOX SNF assemblies are assumed to be of the Westinghouse 17 x 17 design, which is described in Reference 1, Section 2.1. The basis of this assumption is that it maintains consistency with previous work on the disposal of MOX SNF (for example, Ref. 1). This assumption is used throughout Section 5.

3.4 It is assumed that the secondary degradation processes (fission product loss, collapse of assembly fuel pin array, and loss of iron oxide) all proceed at a constant rate, modified by a random fluctuation. The random fluctuation is implemented by adding a random value to the linearly interpolated extent of degradation at each time step in the calculation. The standard deviation of the distribution from which the random value is drawn is nominally set equal to 30 percent of the interpolated extent of degradation. The bases for this assumption are that (a) a constant rate is a convenient initial approximation for a highly uncertain process, and (b) a random fluctuation is added to recognize that conditions in the waste package can change with time and degradation rates may not remain constant. The basis of the assumed size of the random fluctuation (30 percent of the calculated degradation) is that it introduces a significant variation in degradation rates. To examine the sensitivity of the results of the calculation to the size of the random fluctuations, a sensitivity analysis is performed in which the standard deviation of the random fluctuation is assumed to be 70 percent of the interpolated degradation for losses of iron oxide and fission products. This assumption is used throughout Section 5.

3.5 Principal Isotope burnup credit is assumed to be an acceptable method to account for reduced reactivity of MOX SNF in criticality evaluations. The basis for this assumption is Controlled Design Assumption Key 009 (Ref. 10, p. 3-22). This assumption was used to produce input files for the calculations from which the criticality lookup tables in Attachment V were taken (Ref. 9, Section 5.1; Ref. 11, Assumptions 3.1 and 3.2). This assumption is used throughout Section 5.

3.6 It is assumed that the time since emplacement is equal to the time since discharge of the SNF. In other words, it is assumed that the SNF is emplaced in the repository immediately upon discharge from the reactor. The basis for this assumption is the observation that the time between discharge and emplacement (less than 100 years) is negligible compared to the time from emplacement to criticality (more than 10,000 years according to this calculation). This assumption is used throughout Section 5.

3.7 It is assumed that the waste package is horizontally emplaced and floods instantaneously upon breach on the upper side, and drains instantaneously upon breach on the bottom. The basis for this assumption is the evaluation of waste package filling and draining times performed in Reference 12 (pp. 38-41) which indicated that the filling and draining times are relatively short (a few tens to hundreds of years) in comparison to the potential duration of flooding discussed in Section 5.1.3 of this calculation and the 1,000-year time step typically used in the mass-balance calculations. This assumption is used throughout Section 5.

3.8 It is assumed that the Viability Assessment (VA) waste package design, for 21 PWR assemblies is appropriate for determining the probability distribution of breach times and flooding duration. The basis for the first part of this assumption (VA design) is that it is conservative. The earliest time to breach for the VA design is less than 20,000 years (Ref. 6, Figure 5.1.4-1), while the earliest breach time for the newer Enhanced Design Alternative II (EDA II) design is greater than 100,000 years (Ref. 5, Section 5.1.2), which is beyond the time horizon for this calculation. Furthermore, evaluation of the probability of criticality for the EDA II design will be done in FY2000. The basis for the second part of this assumption (21 PWR) is that the Westinghouse design uses the standard 21 PWR waste package and that it is conservative because some waste packages (WPs) will contain fewer assemblies. This assumption is used throughout Section 5.

3.9 It is assumed that the duration of waste package flooding is independent of waste package breach time. The Total System Performance Assessment (TSPA) results discussed in Reference 6 (pp. 16-17) show that there is a positive correlation of flood duration and waste package breach time. This assumption is conservative in the early years because assuming independence implies longer flood duration at early breach times than would occur if flood duration and breach time were positively correlated. On the other hand, assuming independence implies shorter flood duration in later years, which is not conservative in the later years. Flooding during the earlier years is of greater concern due to the expectation that the peak postclosure k_{eff} (Ref. 13, p. 48) will occur in the early years between 10,000 and 35,000 years after closure. Therefore, the basis of this assumption is that it is conservative because it allows for longer flood duration during the more important early years. This assumption is used throughout Section 5.

3.10 It is assumed that an appropriate CL for MOX SNF is CL = 0.92. This value is much lower than that presently being used for ordinary commercial PWR SNF. The basis for this assumption is that the necessary calculations of bias and uncertainty for MOX SNF have less supporting experimental data (in the form of benchmarks and radiochemical assays) than have been available for ordinary commercial SNF. This assumption is used throughout Section 5.

4. USE OF COMPUTER SOFTWARE AND MODELS

4.1 SOFTWARE APPROVED FOR QA WORK

None used.

4.2 SOFTWARE ROUTINES

The Monte Carlo mass balance calculation was performed on a Pentium II personal computer using a C programming language software routine "montecarlomox.c," Version 1. The function of "montecarlomox.c" is to (a) select a set of inputs by randomly sampling the probability distributions that describe the repository environment and waste package degradation (Section 5.1) and (b) using the selected inputs, perform a deterministic mass balance to determine whether a waste package exceeds the CL for the selected inputs. This sampling and calculating process is repeated a specified number of times, resulting in a number of possible outcomes or realizations. Further discussion on the operation of "montecarlomox.c" is provided in Section 5.2.

The implementation of the Monte Carlo process is independently verified as part of the technical check of this calculation. The source code for "montecarlomox.c" is provided in Attachment II. The input and output files for the "montecarlomox.c" scenarios that were run for this calculation are included as Attachments III and IV.

4.3 MODELS

None used.

5. CALCULATION

5.1 CALCULATION INPUT

5.1.1 Probability that a Waste Package is Located Under a Dripping Fracture

The probability that a waste package is located under a dripping fracture is taken to be 0.26 (Ref. 7, Table 4-4).

5.1.2 Time of Waste Package Breach

The parameters of an estimated Weibull cumulative distribution function (CDF) of waste package breach times for waste packages under dripping fractures were obtained from Reference 6, p. 15. The data used to estimate the CDF was developed using the WAPDEG v3.06 code (Ref. 14, pp. 5 through 9, 24). The WAPDEG output for each case lists the times that first penetrations occur on the top and bottom of the waste package (above and below the centerline) both for parts of the waste package under the drip and parts not under the drip. The WAPDEG output contains this information for a sample of 400 waste packages. Under the convention adopted here, breaches on the top of the waste package are required to allow dripping water to enter. Therefore, the earliest time of *any* top penetration was used as the waste package breach time. This is conservative because only top breaches directly under a drip would be expected to allow significant amounts of water to enter the waste package.

The Weibull distribution was chosen for this application because of its ability to fit a wide variety of distribution shapes. The probability density function (pdf) of the Weibull distribution is given by:

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t-\theta}{\alpha}\right)^{\beta-1} \exp\left[-\left(\frac{t-\theta}{\alpha}\right)^{\beta}\right] \quad \text{for } t \geq \theta \qquad \text{(Eq. 5-1)}$$

where α, β, and θ respectively represent the scale, shape, and location parameters (Ref. 15, p. 77). The location parameter gives the lower end of the range over which the equation defines the distribution. For $t < \theta$, the probability density is defined to be zero. Thus, the location parameter shifts the time of earliest possible failure. All of the Weibull parameters are defined to be nonnegative. The associated Weibull CDF is given by:

$$F(t) = 1 - \exp\left[-\left(\frac{t-\theta}{\alpha}\right)^{\beta}\right] \quad \text{for } t \geq \theta. \qquad \text{(Eq. 5-2)}$$

for $t \geq \theta$. For $t < \theta$, $F(t)$ is defined to be zero. The Weibull parameters for waste package breach time are given in Table 5-1. Figure 5-1 (Ref. 6, Figure 5.1.4-1) shows the data and the fitted Weibull CDF for the waste package breach time.

Table 5-1. Weibull Parameters for WP Breach Time and Flood Duration

Characteristic	α	β	θ	Flood Probability
Breach Time	12.099	16.425	0.000	Not Applicable
Flood Duration	10.849	8.228	0.000	0.4775

Source: Reference 6, p. 15.

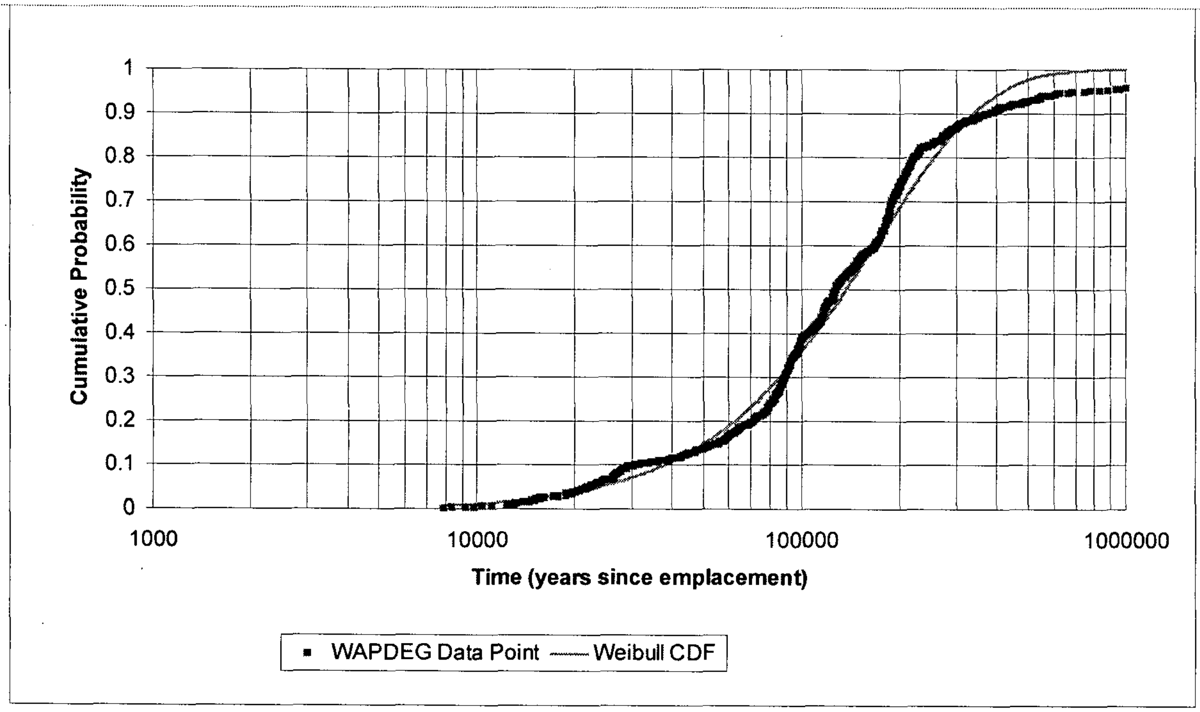

Figure 5-1. Cumulative Distribution of WP Breach Time

5.1.3 Probability And Duration Of Waste Package Flooding

The parameters of an estimated Weibull CDF of the duration of waste package flooding for waste packages under dripping fractures (Table 5-1, Figure 5-2) was obtained from Reference 6 (p. 16). As indicated in Section 5.1.2, the WAPDEG output contains information on the time of penetration of both the top and bottom surfaces of the waste package. In order for the waste package to be capable of accumulating water, it must be penetrated on the top surface, and not on the bottom surface. To obtain a distribution for the possible duration of this "bathtub" condition, the time difference, Δt, between the earliest top penetration, and the earliest bottom penetration, was calculated in Reference 6 (p. 16) for each of the 400 waste packages modeled in the WAPDEG output files. A little over half the waste packages had a negative Δt, indicating that they were penetrated on the bottom first. Thus, at the time of top breach, the waste packages that had been penetrated at the bottom first would be incapable of accumulating water. The fraction of waste packages with positive Δt is indicated as "flood probability" in Table 5-1.

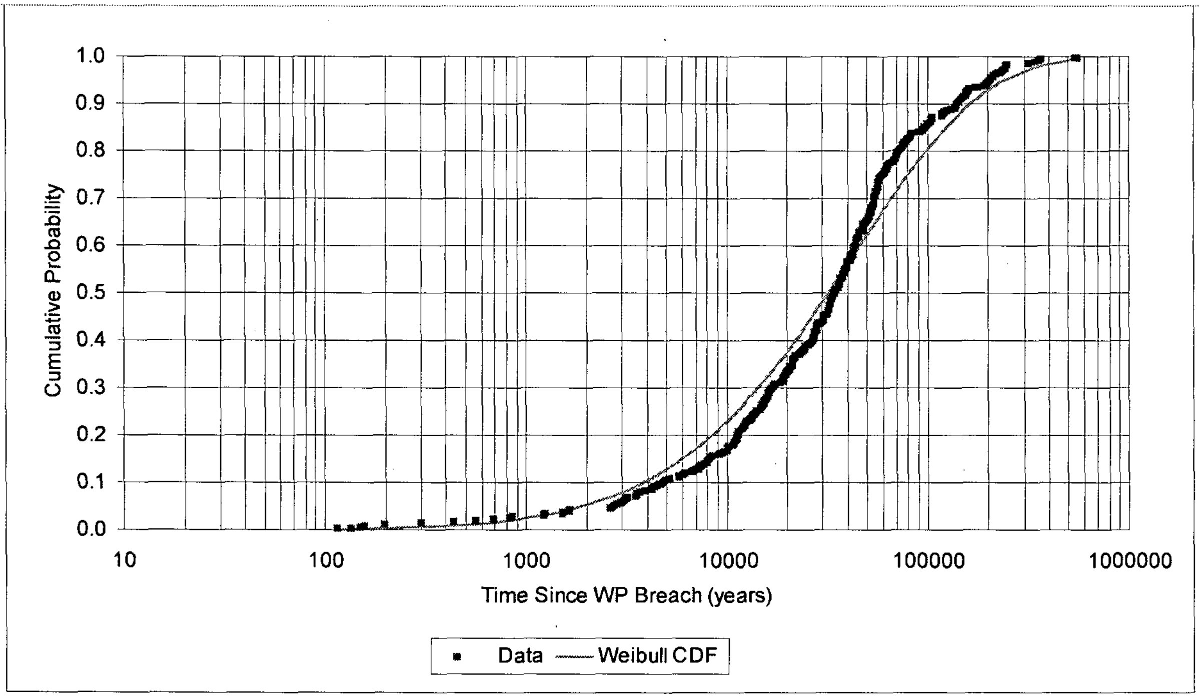

Figure 5-2. Cumulative Distribution of WP Bathtub Duration

5.1.4 Summary of the Westinghouse MOX Assembly Characteristics and Quantities

Conceptual designs for the use of surplus plutonium that has been withdrawn from the U.S. nuclear weapons stockpile as MOX fuel in commercial power reactors have been developed for PWRs (Ref. 1, p. 2). The design used in this calculation is based on the Westinghouse 17 x 17 Vantage 5 commercial fuel assembly (Assumption 3.3). Thirty-two metric tons (MT) of surplus plutonium are suitable for incorporation into MOX assemblies for commercial reactors (Ref. 1, p. 8). With the MOX design based on Westinghouse Vantage 5, there is an average of 18.48 kg of plutonium per assembly; therefore, approximately 1732 MOX assemblies will be required to consume to 32 MT of plutonium (Ref. 1, p. 8). At 21 assemblies per WP (Assumption 3.8), 83 WPs would be required to dispose of the 1732 assemblies.

5.1.5 Nominal Distributions of Secondary Degradation Processes

As mentioned in Section 2, the primary degradation processes, that is, corrosion of the basket materials (carbon steel, borated stainless steel, and aluminum) are assumed to take place initially (Figure 2-1A through Figure 2-1C). Criticality is precluded after the loss of boron provided (a) the assemblies are intact and (b) the fission products and corrosion products (except boron) have not been leached out of the WP (Ref. 9, Tables 6-1 and 6-6). Therefore, the calculation begins with the assumption that the basket materials have completely degraded but remain in the WP and the boron has leached from the WP (Assumption 3.2). Three secondary degradation processes are considered in this calculation: assembly collapse, fission product loss, and iron oxide loss. Each of these is assumed to proceed at a constant rate between specified start and finish times (Assumption 3.4). None of the secondary degradation processes is likely to take place in the first 100,000 years following emplacement. Nevertheless, this calculation investigates the sensitivity of the probability of criticality to the assumed time of occurrence. The nominal or baseline start times for all three processes are generated randomly according to a uniform distribution between 10,000 and 20,000 years, while the nominal finish times are generated randomly according to a uniform distribution between 80,000 and 90,000 years. Variations on this nominal scenario are generated by overriding the parameters of the start- and finish-time distributions with more conservative values.

5.1.6 Table of k_{eff} Values Used in this Calculation

The calculations in this document use one of two modes of analysis according to which pair of degradation parameters is being varied. The first mode allows variation of assembly collapse (as measured by the spacing, or pitch, between fuel pins) and fission product loss. Two hundred values of k_{eff} covering the appropriate range of these two parameters are given in Attachment V, Table V-1. The second mode has variation of pitch and loss of iron oxide. Forty values of k_{eff} covering the appropriate range of these two parameters are given in Attachment V, Table V-2.

The lines of the k_{eff} tables must be arranged so that the sequence of parameters listed corresponds to the frequency of cycling, with a later listed parameter cycling faster than the earlier listed parameter. In addition, the cycles must go from low value to high. The order for the fission-product-loss scenarios is enrichment, pitch, time, and fission product loss. The order for the oxide-loss scenarios is enrichment, pitch, time, and iron oxide loss.

5.2 PROCEDURE

As mentioned in Section 2, the procedure for estimating the probability of criticality for the MOX SNF waste stream is to use the software routine "montecarlomox.c," which is listed in Attachment II. This software routine implements a Monte Carlo technique for generating parameter values to use for inputs to a simple numerical integration of mass balance equations over discrete time steps up to 100,000 years.

The input data used by the software routine are of two types: specific waste package design parameter values (e.g., dimensions, volumes, and masses) and parameters specifying distributions from which random values are sampled for the Monte Carlo realizations. Default values of these parameter values are hard coded into the software routine, but they can be overridden by values entered in the input file "params.in," which thereby serves as a record of values used for sensitivity exercises. Examples of this file are given in Attachment III. In this file there is one line for each override. The override line begins with the name of the parameter to be overridden preceded by the '$' character and followed by an equal sign which is then followed by the numerical value to be assigned as override. The value may be followed by one, or more, blank spaces, which can then be followed by a comment indicating the purpose of the override. This override input technique is similar to the namelist input of FORTRAN. This input file can also contain comment lines, which are indicated by an '*' in the first column.

The Monte Carlo methodology is efficiently implemented by setting up two tables from the criticality calculations presented in Reference 9 (Section 5.1). One table is for the 200 cases with fission product loss (Table V-1), and the other is for the 40 cases with iron oxide loss (Table V-2). Each of these tables contains equal numbers of cases for the two batches of MOX fuel that have significant criticality potential: (1) 304 assemblies with initial 4% ^{239}Pu loading and 35.5 GWd/MTHM burnup and (2) 76 assemblies with initial 4.5% ^{239}Pu loading and 39.3 GWd/MTHM burnup. The methodology implicitly assumes that the waste package is homogeneously loaded with assemblies having the same burnup and initial Pu, so these numbers imply approximately 15 and 4 waste packages, respectively. The remaining assemblies out of the total of 1732 can be seen to be non-critical in the analysis of Reference 1 (p. 3).

For this calculation each of the batches has 30,000 realizations. Each realization begins with two random selections, which are based on the probabilities of their respective events. The first selection is for whether the waste package is dripped on. If the waste package is not dripped on another realization is tried. If the waste package is dripped on, the next selection is for whether the waste package breaches first from the top (which means it can form a bathtub). If not, the next realization is tried.

For those realizations that pass this screening, the parameters of the degradation scenario are generated according to their respective probability distributions. The principal parameters generated in this manner are breach time, bathtub duration, and start and finish times for the assembly collapse process, fission product loss, and iron oxide loss. Then the data for each successive time step are generated. These data include the time-dependent values of the secondary degradation parameters (for which fixed start and finish times were generated earlier): fission product loss, pitch between fuel pins, and loss of iron oxide. Each of these is generated in a two-step process. First, a preliminary value is computed by interpolating between the start and finish time of the process. Next, a fluctuation is added, which is distributed according to a normal distribution with zero mean. The standard deviation, or amplitude, of this fluctuation is an input parameter. After these parameters are generated, the k_{eff} is calculated by table lookup and interpolation. For the fission product loss scenarios, the lookup table consists of 200 lines (k_{eff} values) in the file "ktable.in." For the iron oxide loss scenario, the lookup table consists of 40 lines in the file "koxloss.in." Both these files are given in Attachment V.

If k_{eff} exceeds the potential CL, then a criticality will be recorded. For this purpose, the total number of criticalities is incremented by the number of assemblies in the batch (304 or 76). It should be noted that the criticality is for a waste package, but the bookkeeping is on a per assembly basis for convenience, since neither batch leads to an integral number of waste packages. The expected number of waste package criticalities will be computed by dividing the number of artificial *assembly criticalities* by the number of assemblies per waste package, 21.

The occurrence of a criticality is also logged according to the time of occurrence of the criticality using an array of bins, with one bin for each time step. For this purpose, the bin corresponding to this time step is also incremented by the number of assemblies in the batch. The simulation then moves to the next realization. If, on the other hand, the $k_{eff} < CL$, then the simulation moves to the next time step. If the time steps reach to the duration of the bathtub, the realization is considered to have had no criticality, and the next realization will begin.

After all the realizations have been processed for both batches, the summary statistics can be generated over the time period covered, 100,000 years. The fraction of assemblies participating in a criticality is determined by dividing the total number of criticalities by the number of chances for criticality. This number of chances is the product of two factors: the total number of assemblies, and the number of Monte Carlo realizations. This accounting considers the assemblies that did not pass the k_{eff} screening threshold on the same basis as those that did. The probability density function (pdf, more properly called a frequency function, ff, since the distribution is characterized by discrete time steps) is similarly computed by dividing the number of criticalities in each bin by the same number of chances for criticality. The CDF as a function of time is then calculated by summing the pdf's to that point in time. Although this fraction has been calculated as a fraction of assemblies that could be critical, it is equally valid as a fraction of waste packages since x% of assemblies would also be x% of waste packages. The expected number of waste packages that will experience criticality is then the fraction of waste packages that become critical (which is the probability of criticality) multiplied by the total number of waste packages (which is the total number of assemblies divided by the number of assemblies per waste package, 21).

The summary output file "montecarlo.out" (Attachment IV) contains the date of the run, a descriptive title, and the expected number of criticalities for each 1,000-year time step. The output summary also reports the number of batches screened into Monte Carlo processing and the number of waste packages calculated for the observed number of assemblies. The number of waste packages is the same for all scenarios, so it is used as a check on each run.

As with all Monte Carlo codes, the random numbers are generated by a pseudo-random sequence generated by an algorithm in the code. By default this algorithm will generate the same sequence each time it is run; furthermore, since the sequence is only pseudo-random, it will repeat after some large number of steps. With this default, the program will produce the same statistics every time it is run with a specific set of input parameters in "params.in". The C compiler can start this sequence at an arbitrary point, which is called seeding. The program "montecarlomox.c" can select the seed randomly by using the computer's internal clock time as the argument of the seeding function (srand). In order to ensure reproducibility, the nominal scenarios do not use random seeding.

6. RESULTS

The results of the probability calculations can be summarized in terms of expected number of criticalities in 100,000 years. These are given in Table 6-1 together with a brief characterization of the key parameters for 12 scenarios. An analysis of the results for each scenario follows the table. Note that the scenarios are all very conservative for reasons given in the previous discussions (Sections 2 and 5.2); the scenario with the highest number for expected criticalities, Scenario 8, has two very unlikely conditions: iron oxide loss before 35,000 years, and no assembly collapse before 100,000 years. No attempt is made to present the results of the most conservative combination of parameter values. Instead, variations from the conservative nominal scenarios (Scenarios 1 and 5) are considered to show the effect of variations in each parameter.

Table 6-1. Expected Number of Criticalities for 83 MOX Waste Packages

Scenario Number	Characteristics of the Scenario					Number of Criticalities at 100,000 yr
	Fission Product Loss	Assembly Collapse	Iron Oxide Loss	CV for Fission Product Loss	CV for Iron-Oxide Loss	
1	*	*	None	*	*	0
2	*	None	None	*	*	0.0157
3	Early	*	None	*	*	0.0066
4	Early	None	None	*	*	0.0804
5	None	*	*	*	*	0
6	None	None	*	*	*	0.0019
7	None	*	Early	*	*	0.0078
8	None	None	Early	*	*	0.0653
9	*	*	None	High	*	0
10	*	None	None	High	*	0.0432
11	None	*	*	*	High	0
12	None	None	*	*	High	0.0134

*Nominal values assumed. See Section 5.1.5 for nominal start times of fission product loss, assembly collapse, and iron oxide loss. See Assumption 3.4 for nominal Coefficients of Variation (CV).

The least conservative scenarios are 1 and 5. They can be considered as the nominal or baseline scenarios with respect to fission product loss and iron oxide loss. They are called nominal scenarios because they show these very unlikely processes taking place during the first 100,000 years. Because neither of the nominal scenarios show any criticality in 100,000 years in any of the 60,000 Monte Carlo realizations, scenarios that are even more conservative are examined for comparison to the nominal scenarios. Note not only that some loss of fission products or iron oxide is required, but that the loss must occur early (before 50,000 years) or collapse must be delayed beyond 100,000 years for criticality to be possible.

Scenarios 1 through 4 examine the effects of fission product loss (FPL). Scenarios 2 through 4 represent variations on Scenario 1 that are even more conservative. In these scenarios, early fission product loss means all the fission product neutron absorbers are lost from the waste package by 50,000 years. No collapse means that the start of any reduction in assembly pitch is delayed beyond 100,000 years. These conditions can be verified from the associated input files in Attachment III. Scenario 4 gives the highest expected number of criticalities, as would be expected, since it is the one with two very unlikely conditions: early fission product loss without any assembly collapse. The increase in expected number of criticalities with time for these three alternative scenarios (2, 3, and 4) is shown in Figure 6-1. This figure shows that the expected number of criticalities remains constant after approximately 60,000 years for all three scenarios. This is because the k_{eff} decreases with time beyond 25,000 years due to the decay of the more reactive fissile isotope, ^{239}Pu, to the less reactive isotope, ^{235}U.

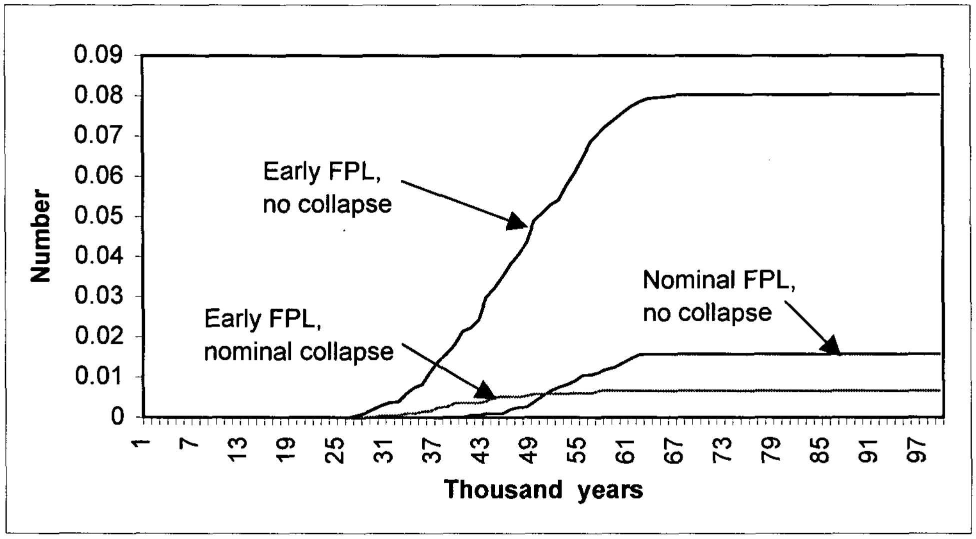

Figure 6-1. Expected Numbers of Criticalities for the Nominal and Alternative Scenarios

Scenarios 5 through 8 examine the effects of iron oxide loss. Since the nominal iron oxide loss scenario (Scenario 5) shows no criticality, the more conservative alternatives Scenarios 6 through 8 are examined. In these scenarios, early iron oxide loss means all the iron oxide is lost from the waste package by 35,000 years. As before, no collapse means that the start of any reduction in assembly pitch is delayed beyond 100,000 years. These conditions can be verified from the associated input files in Attachment III. The results for Scenarios 6 through 8 are of approximately the same order of magnitude as the corresponding results for Scenarios 2 through 4. The detailed time history of criticality occurrence is shown in Figure 6-2. Scenarios 6 through 8 also show no increase in the number of criticalities beyond 60,000 years.

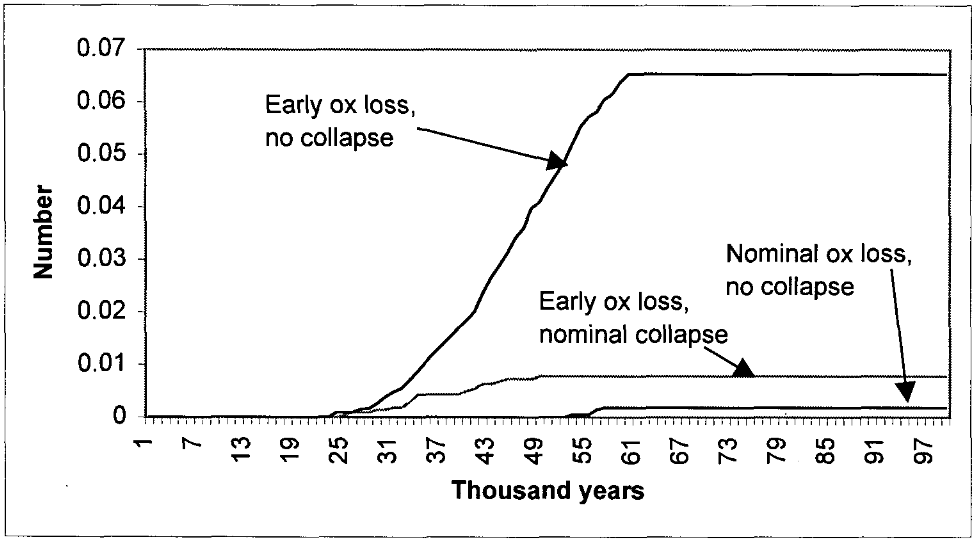

Figure 6-2. Expected Numbers of Criticalities for Alternative Iron-Oxide-Loss Scenarios

Sensitivity analysis for this calculation is performed with respect to the spread in the distribution of random uncertainty that is added to the linear interpolation for the two degradation parameters, fission product loss and iron oxide loss. The amount of this spread is determined by the coefficient of variation (CV), which is the ratio between the standard deviation and the mean of the normal distribution generating the values of the parameter in question. The nominal value for the coefficient of variation is 0.3 for all three of the secondary degradation parameters. The sensitivity of the results to the coefficient of variation is tested by increasing this value to 0.7 for fission product loss in Scenarios 9 and 10 and for iron-oxide loss in Scenarios 11 and 12 (Table 6-1). Scenarios 9 and 11 show no criticalities, indicating that increasing the coefficient of variation does not significantly increase the probability of criticality if the corresponding scenarios for the lower coefficient of variation (Scenarios 1 and 5, respectively) show no criticality. However, Scenarios 10 and 12 do show significant increase in expectation of criticality over the corresponding scenarios with lower coefficient of variation, Scenarios 2 and 6 (Figure 6-3).

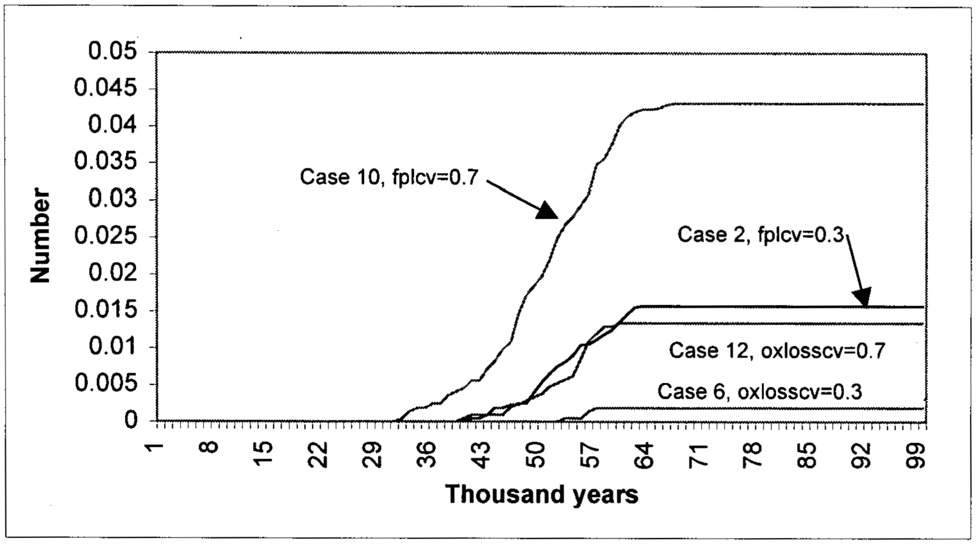

Figure 6-3. Expected Numbers of Criticalities with Alternative Coefficients of Variance for Loss of Oxide and Fission Products

7. ATTACHMENTS

Table 7-1 provides a list of attachments.

Table 7-1. List of Attachments

Attachment Number	Description of Contents	Extent of Attachment
I	Document Input Reference Sheets (DIRS)	3 pages
II	Source code listing for "montecarlomox.c"	11 pages
III	Input files ["params.in"] used for all the scenarios in this calculation	5 pages
IV	Output files "montecarlo.out"	19 pages
V	K_{eff} lookup tables, "ktable.in" and "koxloss.in"	5 pages

8. REFERENCES

1. CRWMS M&O (Civilian Radioactive Waste Management System Management and Operating Contractor) 1998. *Report on Intact and Degraded Criticality for Selected Plutonium Waste Forms in a Geologic Repository, Volume I: MOX SNF.* BBA000000-01717-5705-00020 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19981217.0113.

2. CRWMS M&O 1999. *Probability Calculation Update for EDA II Waste Package Design.* CAL-UDC-MD-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990920.0240.

3. Toledo Edison 1998. Table 4.2-1 Fuel Assembly Dimensions and Materials and Table 4-1 Fuel Design Parameters and Addendum 1, Unit 1, Cycle 12-Reload report from *Davis-Besse Nuclear Power Station No. 1: Updated Safety Analysis Report, Vol. 6.* Rev. 21. Toledo, Ohio: Toledo Edison. TIC: 245410.

4. CRWMS M&O 1998. *Summary Report of Commercial Reactor Criticality Data for Crystal River Unit 3.* B00000000-01717-5705-00060 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980728.0189.

5. CRWMS M&O 1999. *Probability of PWR UCF WP Postclosure Criticality for Enhanced Design Alternatives.* BBA000000-01717-0210-00072 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990927.0365.

6. CRWMS M&O 1998. *Probability of a PWR Uncanistered Fuel Waste Package Postclosure Criticality.* BBA000000-01717-0210-00010 REV 00. Las Vegas Nevada: CRWMS M&O. ACC: MOL.19980806.0607.

7. DOE (U.S. Department of Energy) 1998. *Disposal Criticality Analysis Methodology Topical Report.* YMP/TR-004Q. REV 00. Las Vegas Nevada: DOE. ACC: MOL.19990210.0236.

8. DOE 1998. *Viability Assessment of a Repository at Yucca Mountain: Preliminary Design Concept for the Repository and Waste Package.* Vol. 2. DOE/RW-0508. Las Vegas, Nevada: DOE. ACC: MOL.19981007.0029.

9. CRWMS M&O 1999. *Evaluation of Internal Criticality of the Plutonium Disposition MOX SNF Waste Form.* CAL-EBS-NU-000005 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990928.0238.

10. CRWMS M&O 1998. *Controlled Design Assumptions Document.* B00000000-01717-4600-00032 REV 05. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980804.0481.

11. CRWMS M&O 1998. *Criticality Evaluation of Intact and Degraded PWR WPs Containing MOX SNF.* A00000000-01717-0210-00002 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980701.0482.

12. CRWMS M&O 1996. *Second Waste Package Probabilistic Criticality Analysis: Generation and Evaluation of Internal Criticality Configurations.* BBA000000-01717-2200-00005 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19960924.0193.

13. CRWMS M&O 1997. *Criticality Evaluation of Degraded Internal Configurations for the PWR AUCF WP Designs.* BBA000000-01717-0200-00056 REV 00. Las Vegas Nevada: CRWMS M&O. ACC: MOL.19971231.0251.

14. CRWMS M&O 1998. *Software Routine Report for WAPDEG (Version 3.09).* DI: 30048-2999 REV 02. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19981012.0224.

15. Modarres, M. 1993. *What Every Engineer Should Know About Reliability and Risk Analysis.* New York, New York: Marcel Dekker. TIC: 238168.

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
DOCUMENT INPUT REFERENCE SHEET

1. Document Identifier No./Rev.:	Change:	Title:
CAL-EBS-NU-000007 REV 00	N/A	Probability of Criticality for MOX SNF

Input Document			4. Input Status	5. Section Used in	6. Input Description	7. TBV/TBD Priority	8. TBV Due To		
	2. Technical Product Input Source Title and Identifier(s) with Version	3. Section					Unqual.	From Uncontrolled Source	Un-confirmed
2a 1	CRWMS M&O (Civilian Radioactive Waste Management System Management and Operating Contrator) 1998. *Report on Intact and Degraded Criticality for Selected Plutonium Waste Forms in a Geologic Repository, Volume I: MOX SNF.* BBA000000-01717-5705-00020 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19981217.0113.	p. 2, §2.1	N/A	1, 3, & 5	Identification of Westinghouse MOX design.	N/A	N/A	N/A	N/A
		pp. 38-42	N/A	2	Reference to earlier criticality results.	N/A	N/A	N/A	N/A
		p. 3, pp. 39, 41	TBV-3030	2, 5	Identification of assemblies that could become critical.	3	X	N/A	N/A
		p. 8	TBV-3041	5	Quantity of Pu suitable for incorporation into MOX and the quantity of MOX assemblies required to consume the Pu.	3	X	N/A	N/A
2	CRWMS M&O 1999. *Probability Calculation Update for EDA II Waste Package Design.* CAL-UDC-MD-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990920.0240.	Sections 2 & 5.2	N/A	1	Description of Monte Carlo method used for ordinary commercial SNF.	N/A	N/A	N/A	N/A
3	Toledo Edison 1998. Table 4.2-1 Fuel Assembly Dimensions and Materials and Table 4-1 Fuel Design Parameters and Addendum 1, Unit 1, Cycle 12-Reload report from *Davis-Besse Nuclear Power Station No. 1: Updated Safety Analysis Report, Vol. 6.* Rev. 21. Toledo, Ohio: Toledo Edison. TIC: 245410.	Table 4.2-1	TBV-3070	2	Thickness of the zircaloy spacer grids. Requires acceptance.	3	X	N/A	N/A
4	CRWMS M&O 1998. *Summary Report of Commercial Reactor Criticality Data for Crystal River Unit 3.* B00000000-01717-5705-00060 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980728.0189.	p. 26	TBV-3144	2	Thickness of the zircaloy fuel pin cladding.	3	X	N/A	N/A
5	CRWMS M&O 1999. *Probability of PWR UCF WP Postclosure Criticality for Enhanced Design Alternatives.* BBA000000-01717-0210-00072 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990927.0365.	Section 2	N/A	2	Prior use of the degradation scenario for commercial PWR criticality probability.	N/A	N/A	N/A	N/A
		§ 5.1.2	TBV-3146	3	Time of earliest breach of EDAII WP.	3	X	N/A	N/A

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DOCUMENT INPUT REFERENCE SHEET

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CAL-EBS-NU-000007 REV 00	N/A	Probability of Criticality for MOX SNF

Input Document			4. Input Status	5. Section Used in	6. Input Description	7. TBV/TBD Priority	8. TBV Due To		
	2. Technical Product Input Source Title and Identifier(s) with Version	3. Section					Unqual.	From Uncontrolled Source	Un-confirmed
6	CRWMS M&O 1998. *Probability of a PWR Uncanistered Fuel Waste Package Postclosure Criticality*. BBA000000-01717-0210-00010 REV 00. Las Vegas Nevada: CRWMS M&O. ACC: MOL.19980806.0607.	Section 2	TBV-3177	2	Prior use of the degradation scenario for commercial PWR criticality probability.	3	X	N/A	N/A
		pp. 16-17	TBV-3181	3	Support for claim of positive correlation between breach time and flood duration.	3	X	N/A	N/A
		p. 15	TBV-3182	3, 5	Time of earliest VA WP breach. CDF of waste package top-breach times for waste package under dripping fractures.	3	X	N/A	N/A
						3	X	N/A	N/A
		p. 16	TBV-3183	5	CDF of the duration of waste package flooding for waste packages under dripping fractures.	3	X	N/A	N/A
		p. 16	N/A	5	Method of calculating flood duration.	N/A	N/A	N/A	N/A
7	DOE (U.S. Department of Energy) 1998. *Disposal Criticality Analysis Methodology Topical Report.* YMP/TR-004Q. REV 00. Las Vegas Nevada: DOE. ACC: MOL.19990210.0236.	pp. 3-11 thru 3-13	N/A	2	Degradation analysis method.	N/A	N/A	N/A	N/A
		Table 4-4	TBV-3184	5	Probability that a waste package is located under a dripping fracture.	3	X	N/A	N/A
8	DOE 1998. *Viability Assessment of a Repository at Yucca Mountain: Preliminary Design Concept for the Repository and Waste Package*. Vol. 2. DOE/RW-0508. Las Vegas, Nevada: DOE. ACC: MOL.19981007.0029.	p. 4-23	TBV-3185	3	Support for the assumption that the waste package is rendered inert with helium before sealing.	3	X	N/A	N/A
9	CRWMS M&O 1999. *Evaluation of Internal Criticality of the Plutonium Disposition MOX SNF Waste Form*. CAL-EBS-NU-000005 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990928.0238.	§5.1, Tables 6.1-1 thru 6.1-10, 6.2-1, 6.2-2	TBV-3186	3, 5, Att. V	Criticality calculation results. Support for assumption that Westinghouse design is appropriate. Support for the assumption that there will be no criticality before complete degradation. Evidence that principal isotope burnup credit was taken in the criticality calculations. Criticality lookup tables.	3	X	N/A	N/A

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DOCUMENT INPUT REFERENCE SHEET

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CAL-EBS-NU-000007 REV 00	N/A	Probability of Criticality for MOX SNF

Input Document							8. TBV Due To		
2. Technical Product Input Source Title and Identifier(s) with Version		3. Section	4. Input Status	5. Section Used in	6. Input Description	7. TBV/TBD Priority	Unqual.	From Uncontrolled Source	Un-confirmed
10	CRWMS M&O 1998. *Controlled Design Assumptions Document.* B00000000-01717-4600-00032 REV 05. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980804.0481.	p. 3-22	TBV-3187	3	Controlled Design Assumption: Key 009, i.e., take credit for principal isotope burnup.	3	X	N/A	N/A
11	CRWMS M&O 1998. *Criticality Evaluation of Intact and Degraded PWR WPs Containing MOX SNF.* A00000000-01717-0210-00002 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980701.0482.	Assump. 3.1 and 3.2	NA	3	Evidence that credit was taken for Principal Isotope burnup in the criticality calculations.	N/A	N/A	N/A	N/A
12	CRWMS M&O 1996. *Second Waste Package Probabilistic Criticality Analysis: Generation and Evaluation of Internal Criticality Configurations.* BBA000000-01717-2200-00005 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19960924.0193.	pp. 38-41	TBV-3188	3	Estimation of waste package filling and draining times.	3	X	N/A	N/A
13	CRWMS M&O 1997. *Criticality Evaluation of Degraded Internal Configurations for the PWR AUCF WP Designs.* BBA000000-01717-0200-00056 REV 00. Las Vegas Nevada: CRWMS M&O. ACC: MOL.19971231.0251.	p. 15, Assump. 4.3.1 p. 48	N/A TBV-3189	3 3	Evidence that Controlled Design Assumption Key 009 (burnup credit) was used in criticality calculations. Time of peak post-closure $k_{eff.}$	N/A 3	N/A X	N/A N/A	N/A N/A
14	CRWMS M&O 1998. *Software Routine Report for WAPDEG (Version 3.09).* DI: 30048-2999 REV 02. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19981012.0224.	pp. 5-9, 24	N/A	5	Description of WAPDEG v3.09 computer program.	N/A	N/A	N/A	N/A
15	Modarres, M. 1993. *What Every Engineer Should Know About Reliability and Risk Analysis.* New York, New York: Marcel Dekker. TIC: 238168.	p. 77	N/A	5	Definition of the Weibull distribution.	N/A	N/A	N/A	N/A

Attachment II. Source code for MONTECARLOMOX.C

```
/* montecarlomox.c  This code is similar to montecarlo.c, with the
   following major differences: (1) It uses only the two MOX PWR
   fuel types that can go critical so there is no need for screening;
     (2) It uses a table lookup and interpolation to calculate keff,
     instead of a regression like was used in montecarlo.c.

     The program operates on the input file, "params.in",
     which contains any overrides on paramers that are nominally
     hard coded.  These overrides are accomplished in a manner similar to the
     FORTRAN namelist.  In the file "params.in" the variable name is preceded
     by a '$' character and then a code line for reading that variable is
   inserted at an appropriate place in the program.  The file "params.in"
     is read in to the array lines[100] (which could be allocated dynamically,
     but will never contain more than 100 lines so why bother).  The lines[]
     array is searched for a match starting in the position 1 of each element
     [line].  At position 0 of each line[] is the '$' character.  This
     capability is extended to arrays of float, with the differences: (1) The
     array name is followed by []; (2) The values on the right side of the '='
     are in a comma separated list;  (3) The last element of the list must be
     followed by a comma, after which there can be comments.

   There are two different forms for comments in the file "params.in":
     (1) Anything after the obligatory fields in a keyword statement;
     (2) Any line that begins with an '*'.  Comments of type 1 are copied into
     the input array of lines, but not included in the read of the line of
     lines[] since each keyword keys a read of only a limited number of fields
     in the array lines[].  Comments of type 2 are simply diverted into the
     debugging file, "junk.out", so there is a record that they have been read
     but not used.

     Since we have identified the only two burnup-enrichment pairs that might
     be capable of criticality, there is no need for preliminary screening.

     The actual criticalities are counted when keff exceeds cl.
     These criticalities are binned according to the time at which they
     occurred (numcrits[]) and tallied in the parameter ntotalcrit.  Since
     these counts are expanded by the number of Monte Carlo realizations (rlztns)
     they are converted to probabilities by dividing by the total number of
     assemblies read (ntotassy) and dividing by the number of realizations
     (rlztns), so that the sample space is expanded to that which it would
     have been if all the assemblies had been subjected to the number of
     realizations.  The pdf and CDF calculated in this manner are thus on a
     per assembly basis.  To convert to a per package basis, we divide by the
     number of assembilies in a waste package, 21.  The expected number of
     criticalities for all the MOX packages is found by multiplying
```

```
    the CDF by ntotassy (which is 1732 for the current MOX design).
    (which has been expanded by multiplication by
    rlztns) and dividing by the number of assembilies in a waste package and
    by the number of realizations.

    At the present time the drip rate is only used to calculate the rate of
    boron removal, which determines the boron in solution. This is of little
    importance because all the boron is removed from solution by the next
    increment following complete corrosion of borated stainless steel. The
    program has the capability to use regressions that come from either the
    uniform or the settled distribution of the iron oxide. However, the
    recent addition of aluminum thermal shunts to the PWR waste package
    limits the space available for oxide settling, so the nominal model
    of waste package degradation assumes a uniform distribution of the iron
    oxide.
*/

#include <string.h>
#include <stdlib.h>
#include <stdio.h>
#include <math.h>
#include <malloc.h>
#include <string.h>
#include <ctype.h>
#include <time.h>
#define NUMBINS 100

float getfloat(),InvNorm(float,float),InvUni(float,float),
  InvLWeib(float,float,float),
  kcalc(float,float,float),//nominal keff table lookup
  kcalco(float,float,float),//oxloss keff table lookup
  findfloat(char*,int,int), //used to find and read float override
  kdelt(float,float,float); //delta keff from oxide loss
int tlookup(float,float*,int); //get index values for tracked parameters
int findint(char*,int,int); //used to find and read int override
int getint(),inc=1000; //integration timestep
int rlztns=100,    //number of Monte Carlo realizations
   dripflag=0;    //0 if one rate (or no drip) for each rlztn,
               //1 if new rate each timestep
char lines[100][100];//for storage of override input file as an array
FILE *ferr,*fout,*fin,*fparams,*fktable;
float prbt=0.4775, //probability of bathtub
     prdrip=0.26,    //probability of drip on any given bathtub
     ex=.1,       //exchange flushing efficiency
     voidsp0=3.733,          //initial voidspace in CSNF pkg, m^3.
     mbwp=30110*.199; //initial boron in BSS in gm
float    keffs[5][5][5][5], //table of cases
```

```
    ts[5],            //lookup table for times
    fpls[5],           //lookup table for fission product loss %
    pitches[5],          //lookup table for pitch values
    oxlosses[5],          //lookup table for fe oxide loss values
    a;              //initial enrichment
int get2(char*,char*,char),look1(float,float*,int);
void etrim(char*),ftrim(char*);
void getfarray(char*,float*,int,int);
float getnum(char*),interp(int,int,int,float,float,float),
  interpf(int,int,int,float,float),interpg(int,int,int,float),
    interpbf(int,int,int,float,float),interpbg(int,int,int,float),
    interpb(int,int,int,float,float,float);


void main()
{int i,j,m,it,k=0,numrisk=0,na,nocrit,nmlns,randflag=0,
  numpkgs=0,          //number of waste packages used
    ntotassy=1732,        //total number of MOX assemblies
    ncrassy[2]={304,76}, //potentially critical assemblies
    usflag=1,          //nominal oxide distribution is uniform
  oxlossflag=0,        //nominal no oxide loss
    fueldegflag=1;      //nominal fuel degradation and FP loss
float x,b,keff,pkeff,t,stime,etime,ptime,kav=0,flow,mav,
  burnup[2]={35,39.5},
    assay[2]={4.0,4.5},
  cl=(float)0.98,
    pitch,
    oxloss, //percent of iron oxide that has left the waste package
    startloss,endloss, //time of start and end of oxide loss process
    clpsts,clpstf,mclps,mfpl,
    btimedist[]={12.099,16.425,0}, //VA breach time alph, beta, theta
    bdurdist[]={10.849,8.228,0}, //VA duration of bathtub alph, beta theta
    fpltsdist[]={10000,20000},//start of fission product loss
    fpltfdist[]={80000,90000},//all fission products lost
    clpstsdist[]={10000,20000},//start of collapse of assemblies
    clpstfdist[]={80000,90000},//all assemblies collapsed
    startoxloss[]={10000,20000},//start time for iron oxide loss
    endoxloss[]={80000,90000},
    flowdist[]={.05,.5},     //Flow min max m^3/yr for uniform distribution
    fplcv=.3,          //CV for fission product (neutron absorber) loss
    clpscv=.3,            //coefficient of variation for assy collapse
    oxlosscv=.3,
    fplts,fpltf;//start and finish times of fission product loss process
long int numcrits[NUMBINS]={0},
  numccrits[NUMBINS]={0}, //to accumulate criticalities in 1000 yr bins
  ntotalcrit=0;
float pdfcrits[NUMBINS]={0},cdfcrits[NUMBINS]={0};
```

```
char buffer[300],title[100];
time_t ltime;                    //variable for date & time
time( &ltime );           //fill ltime structure with current time
ferr=fopen("junk.out","w");       //characteristics of each criticality
if ((fparams=fopen("params.in","r"))==NULL) //overrides for this case
 {printf("Can't open params.in\n");exit(0);}
fgets(title,90,fparams); //first line of parameter file must be title
i=0;     //read parameter overrides for this case into input array lines[]
while((fgets(buffer,90,fparams)!=NULL)&&(i<100))//read overrides
 {if(buffer[0]=='*') fprintf(ferr,"%s",buffer);//divert comment to "junk.out"
 else strcpy(lines[i++],buffer);}
fprintf(ferr,"\n");
nmlns=i;                  //number of override parameter lines
printf("%d parameters read\n",nmlns);
fout=fopen("montecarlo.out","w"); //probability and expected criticalities
fprintf(fout, "The time is %s", ctime( &ltime ) );
if((i=findint("$oxlossflag",0,nmlns))>-1) oxlossflag=i;
if(oxlossflag==0)  //use no  oxloss table
 {if ((fktable=fopen("ktable.in","r"))==NULL) //table of k data
  {printf("Can't open ktable.in\n");exit(0);}
 for(i=0;i<2;i++)          //assay index
  for(j=0;j<5;j++)         //pitch index
    for(k=0;k<4;k++)        //time index
        for(m=0;m<5;m++)       //fpl index
              {fgets(buffer,100,fktable);
         keffs[i][k][m][j]=getnum(buffer);
                x=getnum(buffer);  //we already know the enrichment by i
                pitches[j]=getnum(buffer);
                ts[k]=getnum(buffer);
                fpls[m]=atof(buffer);}
 for(i=0;i<2;i++)          //assay index
  for(j=0;j<5;j++)         //pitch index
   for(k=0;k<4;k++)        //time index
    for(m=0;m<5;m++)      //fpl index
     fprintf(ferr,"%f %f %f %f %f\n",keffs[i][k][m][j],(i==0?4.0:4.5),
        pitches[j],ts[k],fpls[m]);}
else
 {if ((fktable=fopen("koxloss.in","r"))==NULL) //table of oxloss k data
  {printf("Can't open oxloss file\n");exit(0);}
 for(i=0;i<2;i++)          //assay index
  for(j=0;j<2;j++)         //pitch index
    for(k=0;k<2;k++)        //time index
        for(m=0;m<5;m++)       //oxloss index
              {fgets(buffer,100,fktable);
         keffs[i][j][k][m]=getnum(buffer);
                x=getnum(buffer);  //we already know the enrichment by i
                pitches[j]=getnum(buffer);
```

```
            ts[k]=getnum(buffer);
            x=getnum(buffer); //all the fpl's are the same for oxide loss table
            oxlosses[m]=atof(buffer);}
 for(i=0;i<2;i++)         //assay index
  for(j=0;j<2;j++)        //pitch index
   for(k=0;k<2;k++)       //time index
    for(m=0;m<5;m++)      //fpl index
     fprintf(ferr,"%f %f %f %f %f\n",keffs[i][j][k][m],(i==0?4.0:4.5),
        pitches[j],ts[k],oxlosses[m]);}
if((x=findfloat("$prbt",0,nmlns))>-1) prbt=x;
if((x=findfloat("$cl",0,nmlns))>-1) cl=x;
if((x=findfloat("$oxlosscv",0,nmlns))>-1) oxlosscv=x;
if((x=findfloat("$fplcv",0,nmlns))>-1) fplcv=x;
getfarray("$btimedist[]",btimedist,3,nmlns);
getfarray("$bdurdist[]",bdurdist,3,nmlns);
getfarray("$clpstsdist[]",clpstsdist,2,nmlns);
getfarray("$clpstfdist[]",clpstfdist,2,nmlns);
getfarray("$fpltsdist[]",fpltsdist,2,nmlns);
getfarray("$fpltfdist[]",fpltfdist,2,nmlns);
getfarray("$flowdist[]",flowdist,2,nmlns);
getfarray("$startoxloss[]",startoxloss,2,nmlns);
getfarray("$endoxloss[]",endoxloss,2,nmlns);
if((i=findint("$rlztns",0,nmlns))>-1) rlztns=i;
if((i=findint("$randflag",0,nmlns))>-1) randflag=i;
if((i=findint("$fueldegflag",0,nmlns))>-1) fueldegflag=i;
if(randflag==1)
  srand( (unsigned)time( NULL ) ); //random seed for random number generator
for(i=0;i<2;i++)              //for 2 values of enrichment
  {b=burnup[i];
  a=assay[i];
  na=ncrassy[i];     //number of assemblies
  pkeff=0;       //reset peak keff
  for(j=0;j<rlztns;j++)//following lines do bathtub time range from WAPDEG
    {if((dripflag==0)&&(prdrip<(float)rand()/RAND_MAX))continue;
              //this realization of pkg is not dripped on at any time
    stime=InvLWeib(btimedist[0],btimedist[1],btimedist[2]);//breach time
    if(prbt<(float)rand()/RAND_MAX) continue;//breach but no bathtub
    else etime=stime+InvLWeib(bdurdist[0],bdurdist[1],bdurdist[2]);
    t=stime;       //time to start degradation of package components
    nocrit=1;      //no criticality yet
    clpsts=t+InvUni(clpstsdist[0],clpstsdist[1]);//start of assy collapse
    clpstf=t+InvUni(clpstfdist[0],clpstfdist[1]);//finish, from breach time
    fplts=t+InvUni(fpltsdist[0],fpltsdist[1]);//start of fission product loss
    fpltf=t+InvUni(fpltfdist[0],fpltfdist[1]);//finish, from breach time
    startloss=t+InvUni(startoxloss[0],startoxloss[1]);//start of fission product loss
    endloss=t+InvUni(endoxloss[0],endoxloss[1]);//finish, from breach time
    while((t<etime)&&(nocrit==1)&&(t<NUMBINS*inc))//loop until bathtub
```

```
        //duration is exceeded, or criticality occurs, or time limit exceeded
     {if((dripflag==0)||(prdrip>(float)rand()/RAND_MAX))
            flow=InvUni(flowdist[0],flowdist[1]);//flow in m^3/yr
        else flow=0; //pkg not dripped on during this timestep
      if((t>clpsts)&&(t<clpstf)) //calculate percent collapsed
      {mclps = 100*(t - clpsts)/(clpstf - clpsts);//mean value
          mclps=InvNorm(mclps,clpscv*mclps);}//generate actual from normal dist.
     else if (t<=clpsts) mclps=0; //no collapse yet
        else if (t>=clpstf) mclps=100;          //completely collapsed
        if(mclps>100)mclps=100;
        if(mclps<0)mclps=0;
        pitch=mclps*0.9144+(100-mclps)*1.25984;//pitch in .01 cm
        pitch/=100;                   //reduce to cm
        if((t>fplts)&&(t<fpltf))//calculate percent fission product loss
      {mfpl = 100*(t - fplts)/(fpltf - fplts);//mean value
          mfpl=InvNorm(mfpl,fplcv*mfpl);}//generate actual from normal dist.
     else if (t<=fplts) mfpl=0; //no FPL yet
        else if(t>=fpltf) mfpl=100; //complete loss of fission products
        if(mfpl>100)mfpl=100;
        if(mfpl<0)mfpl=0;
      if((t>startloss)&&(t<endloss)) //calculate % iron oxide loss
      {oxloss = 75*(t - startloss)/(endloss-startloss);//Max loss=75%
          oxloss=InvNorm(oxloss,oxlosscv*oxloss);}//generate actual from normal
     else if (t<=startloss) oxloss=0; //no loss yet
        else if (t>=endloss) oxloss=75; //Max iron oxide loss=75%
        if(oxloss>75) oxloss=75;
     if(oxlossflag==0)keff=kcalc(t,mfpl,pitch);
        else keff=kcalco(t,oxloss,pitch);
     if(keff>pkeff) //keep track of the peak keff for this realization
          {pkeff=keff;
          ptime=t;}
     if(keff>cl) //criticality reached for this realization
       {numcrits[(t/inc>NUMBINS-1)?NUMBINS-1:(int)t/inc]+=na;//increment
                  //appropriate timestep bin, or max timestep bin
          ntotalcrit+=na;//increment total criticalities
          nocrit=0;}  //criticality found, end this realization
        t+=inc;}}} //end this timestep,realization, and batch
kav/=ntotassy;
numpkgs=ntotassy/21;
ntotassy*=rlztns; //escalate for number of realizations
fprintf(ferr,"\n\n\n");          //header for log file
fprintf(ferr,"%12s%12s%12s%12s%12s\n","Kyear","pdf","CDF","Crit pkgs","numcr");
fprintf(fout,"%12s%12s\n","Kyear","Crit pkgs");
for(it=1;it<NUMBINS;it++)
 {pdfcrits[it]=(float)numcrits[it]/ntotassy;//convert bins to pdf (or ff)
 numccrits[it]=numccrits[it-1]+numcrits[it];//accumulate number of crits
 cdfcrits[it]=(float)numccrits[it]/ntotassy;  //calculate CDF for this bin
```

```
 fprintf(ferr,"%12d%12.7f%12.7f%12.4f%12ld\n",//statistics for this timestep
    it,pdfcrits[it],cdfcrits[it],cdfcrits[it]*numpkgs,numcrits[it]);
 fprintf(fout,"%12d%12.7f\n",//statistics for transfer to Excel chart
    it,cdfcrits[it]*numpkgs);}
fprintf(ferr,"\n\n");
fprintf(ferr,"10 timestep moving average, to demonstrate smoothing\n");
fprintf(ferr,"%12s%12s\n","Kyear","pdf");
mav=0;                    //reset moving average pdf to zero
for(it=1;it<11;it++)mav+=pdfcrits[it];//initial moving average pdf
mav/=10;
for(it=5;it<NUMBINS-6;it++)
 {fprintf(ferr,"%12d%12.7f\n",it,mav);//print moving average pdf
 mav+=(pdfcrits[it+6]-pdfcrits[it-4])/10;}//moving avg for next timestep
printf("assy read= %ld  critpkg= %f\n",ntotassy,cdfcrits[NUMBINS-1]*numpkgs);
printf("%s",title);
printf("numcrits@10kyrs=%ld exp100=%f\n",numccrits[10],
   cdfcrits[99]*numpkgs);//statistics for this run
fprintf(fout,"%s",title); //output file summary
fprintf(fout,"numcrits@10kyr=%ld exp10=%f exp100=%f\n",numccrits[10],
 cdfcrits[10]*numpkgs,cdfcrits[99]*numpkgs);}

//function to get a float from a specified character substring
float getfloat(char *string, int start, int length)
{char temp[30];
strncpy(temp,string+start,length);
temp[length]='\0';
return((float)atof(temp));}

//function to get an int from a specified character substring
int getint(char *string, int start, int length)
{char temp[30];
strncpy(temp,string+start,length);
temp[length]='\0';
return(atoi(temp));}

float InvNorm (float mean, float stdev)
{float norm=0;
int i;  //construct normal distribution from the central limit theorem
for(i=0;i<12;i++) norm = norm + (float)rand()/RAND_MAX;
norm = norm - 6;
return stdev * norm + mean;}

float InvUni (float min, float max)
{return min + (max - min)*(float)rand()/RAND_MAX;}//uniform distribution

float InvLWeib (float alpha, float beta, float theta)//Weib for log(t)
{float x,y;
```

```
x=(float)rand()/(RAND_MAX+1);
y=-log(1-x);
return exp(theta + alpha*pow(y,1/beta));}

float kcalc(float t,float f,float p)
{int ip,it,ifp;
float keff;
if(t<=ts[0])t=ts[0]+1;
if(f<=fpls[0])f=fpls[0]+.01;
if(p<=pitches[0])p=pitches[0]+.01;
it=look1(t,ts,4);
ifp=look1(f,fpls,5);
ip=look1(p,pitches,5);
keff=interpb(it,ip,ifp,t,p,f);
if(keff>.9)
  {fprintf(ferr,"time=%.0f  pitch=%.3f  fpls=%.0f  keff=%.4f",t,p,f,keff);
  fprintf(ferr,"  ifp=%d\n",ifp);}
return keff;}

float kcalco(float t,float ox,float p)
{int ip,it,iox;
float keff;
if(t<=ts[0])t=ts[0]+1;
if(ox<=oxlosses[0])ox=oxlosses[0]+.01;
if(p<=pitches[0])p=pitches[0]+.01;
it=1;
iox=look1(ox,oxlosses,5);
ip=1;
keff= interp(ip,it,iox,p,t,ox);
if (keff>0.9)
  fprintf(ferr,"time=%.0f oxls=%.0f pitch=%.3f keff=%.4f\n",t,ox,p,keff);
return keff;}

float interp(int i,int j,int k,float x,float y,float z)
{float v;
v= interpf(i,j,k,y,z)*(x-pitches[i-1])+interpf(i-1,j,k,y,z)*(pitches[i]-x);
v/=pitches[i]-pitches[i-1];
return v;}

float interpb(int i,int j,int k,float x,float y,float z)
{float v;
v= interpbf(i,j,k,y,z)*(x-ts[i-1])+interpbf(i-1,j,k,y,z)*(ts[i]-x);
v/=ts[i]-ts[i-1];
return v;}

float interpf(int i,int j,int k,float y,float z)
{float v;
```

```
v=interpg(i,j,k,z)*(y-ts[j-1])+interpg(i,j-1,k,z)*(ts[j]-y);
v/=ts[j]-ts[j-1];
return v;}

float interpbf(int i,int j,int k,float y,float z)
{float v;
v=interpbg(i,j,k,z)*(y-pitches[j-1])+interpbg(i,j-1,k,z)*(pitches[j]-y);
v/=pitches[j]-pitches[j-1];
return v;}

float interpbg(int i,int j,int k,float z)
{float v;
int ia;
ia=(a<4.1?0:1);
v=keffs[ia][i][j][k]*(z-fpls[k-1])+keffs[ia][i][j][k-1]*(fpls[k]-z);
v/=fpls[k]-fpls[k-1];
return v;}

float interpg(int i,int j,int k,float z)
{float v;
int ia;
ia=(a<4.1?0:1);
v=keffs[ia][i][j][k]*(z-oxlosses[k-1])+keffs[ia][i][j][k-1]*(oxlosses[k]-z);
v/=oxlosses[k]-oxlosses[k-1];
return v;}

int look1(float x,float *array,int n)
{int i=0;
while ((i<n)&&(x>array[i]))i++;
return i;}


//Find the float numerical value in a statement that begins with the specified
//keyword (keystr). Presently designed to read from the array lines
float findfloat(char* keystr,int startrow,int numrows)
{int i=0;
char stag[20],tempstr[100];
while ((strncmp(keystr,lines[startrow+i],strlen(keystr))!=0)&&(i<=numrows))
   i++;
if (i==numrows+1) return -1;
strcpy(tempstr,lines[startrow+i]);
get2(stag,tempstr,'=');
return (float)atof(tempstr);}

//Find the int numerical value in a statement that begins with the specified
//keyword (keystr).
int findint(char* keystr,int startrow,int numrows)
```

```
{int i=0;
char stag[20],tempstr[100];
while ((strncmp(keystr,lines[startrow+i],strlen(keystr))!=0)&&(i<=numrows))i++;
if (i>=numrows) return -1;
strcpy(tempstr,lines[startrow+i]);
get2(stag,tempstr,'=');
return atoi(tempstr);}

//copies the strings occurring before and after the separator c (e.g. '=')
int get2(char *stag,char *sdummy,char c)
{int i,index,len;
char *p;
len=strlen(sdummy);
p=strchr(sdummy,c);
i=(int)(p-sdummy);
index=i;
strncpy(stag,sdummy,i);    //copy string before separator
stag[i]='\0';
etrim(stag);
strcpy(sdummy,p+1);       //copy string following separator
i=0;
while((sdummy[i]==' ')&&(i<len))i++;//read through leading blanks
if((i==len)||(sdummy[i]=='\n')) return -1;//can't find a second word on rt side
strcpy(sdummy,sdummy+i); //copy front trimmed string
return index;}

void etrim(char *dummy)//trims trailing blanks
{int i;
i=strlen(dummy)-1;
while(dummy[i]<=32)i--;
dummy[i+1]='\0';}

//trims leading blanks; used in get2 so that fdummy starts with a non-blank
void ftrim(char *dummy)
{int i=0;
while(dummy[i]<=32)i++;
strcpy(dummy,dummy+i);}

//Searches the override array lines[] for a line beginning with the string
//passed in keystr.  If the searchstring (keystr) is not found, it simply
//returns.  Othewise it takes num values in the comma separated list on the
//right side of the '=' and enters them in the float array farray, overriding
//the values that were hard coded.
void getfarray(char *keystr,float *farray,int num,int numrows)
{int i=0;
char stag[20],tempstr[100];
while ((strncmp(keystr,lines[i],strlen(keystr))!=0)&&(i<numrows))
```

```
  i++;
if (i==numrows) return;//searchstring not found, so return
strcpy(tempstr,lines[i]);
get2(stag,tempstr,'=');
for(i=0;i<num;i++) //get all the elements from the comma separated list
 {farray[i]=atof(tempstr);
 strcpy(tempstr,strchr(tempstr,',')+1);}}

float getnum(char *string)
{float x;
char *p;
p=strchr(string,' ');
x=atof(string);
strcpy(string,p+1);
ftrim(string);
return x;}

int tlookup(float x,float *array,int n)
{int i=0;
while ((i<n)&&(x>array[i]))i++;
if((array[i]-x)<(array[i]-array[i-1])/2) return i;
else return i-1;}
```

Attachment III. Input files

Case 1, nominal

```
*VA MOX, cl=.92, nominal: fpl, collapse
*$randflag=1 //randomize using the clock
*$oxlossflag=1 //oxloss case
*$oxlosscv=.7 //coefficient of variance for oxide loss
$pnobt=0.5225 //probability of no bathtub
$cl=0.92
$rlztns=30000 //extra iterations
*$flowdist[]=.05,.05, //current drip rate
*$btimedist[]=2.347,4.810,10.820, //EDA breach time alph, beta, theta
*$bdurdist[]=11.881,10.218,0, //EDA duration of bathtub alph, beta theta
*$clpstsdist[]=100000,120000,
*$clpstfdist[]=100000,120000, // collapse
*$startoxloss[]=10000,10000,// ox loss
*$endoxloss[]=35000,35000,
*$fpltsdist[]=50000,600000, //start of fission product loss
*$fpltfdist[]=100000,120000, //all fission products lost
```

Case 2

```
*VA MOX, cl=.92, nominal fpl,no collapse

*$randflag=1  //randomize using the clock

*$oxlossflag=1 //oxloss  case

*$oxlosscv=.7  //coefficient of variance for oxide loss
$pnobt=0.5225   //probability of no bathtub
$cl=0.92
$rlztns=30000    //extra iterations
*$flowdist[]=.05,.05, //current drip rate
*$btimedist[]=2.347,4.810,10.820,    //EDA breach time alph, beta, theta
*$bdurdist[]=11.881,10.218,0,    //EDA duration of bathtub alph, beta theta
$clpstsdist[]=100000,100000, //no collapse in 100,000 years.
$clpstfdist[]=100000,100000, //
*$startoxloss[]=10000,10000,// ox loss
*$endoxloss[]=35000,35000,
*$fpltsdist[]=50000,600000,  //start of fission product loss
*$fpltfdist[]=100000,120000,  //all fission products lost
```

Case 3

```
*VA MOX, cl=.92, early fpl,nominal collapse

*$randflag=1  //randomize using the clock

*$oxlossflag=1 //oxloss  case

*$oxlosscv=.7  //coefficient of variance for oxide loss
$pnobt=0.5225   //probability of no bathtub
$cl=0.92
$rlztns=30000    //extra iterations
```

```
*$flowdist[]=.05,.05, //current drip rate
*$btimedist[]=2.347,4.810,10.820,   //EDA breach time alph, beta, theta

*$bdurdist[]=11.881,10.218,0,    //EDA duration of bathtub alph, beta theta
*$clpstsdist[]=10000,10000, //early collapse
*$clpstfdist[]=30000,40000, //
*$startoxloss[]=10000,10000,// ox loss
*$endoxloss[]=35000,35000,
$fpltsdist[]=10000,20000,  //start of fission product loss
$fpltfdist[]=40000,50000,  //all fission products lost
```

Case 4

```
*VA MOX, cl=.92, early fpl,no collapse

*$randflag=1  //randomize using the clock

*$oxlossflag=1 //oxloss  case

*$oxlosscv=.7  //coefficient of variance for oxide loss

$pnobt=0.5225   //probability of no bathtub
$cl=0.92
$rlztns=30000    //extra iterations
*$flowdist[]=.05,.05, //current drip rate
*$btimedist[]=2.347,4.810,10.820,   //EDA breach time alph, beta, theta
*$bdurdist[]=11.881,10.218,0,    //EDA duration of bathtub alph, beta theta
$clpstsdist[]=100000,100000, //late collapse
$clpstfdist[]=100000,100000, //
*$startoxloss[]=10000,10000,// ox loss
*$endoxloss[]=35000,35000,
$fpltsdist[]=10000,20000,  //start of fission product loss
$fpltfdist[]=40000,50000,  //all fission products lost
```

Case 5

```
*VA MOX, cl=.92, nominal collapse and oxide loss

*$randflag=1  //randomize using the clock

$oxlossflag=1 //oxloss  case

*$oxlosscv=.7  //coefficient of variance for oxide loss

$pnobt=0.5225   //probability of no bathtub
$cl=0.92
$rlztns=30000    //extra iterations
*$flowdist[]=.05,.05, //current drip rate
*$btimedist[]=2.347,4.810,10.820,   //EDA breach time alph, beta, theta
*$bdurdist[]=11.881,10.218,0,    //EDA duration of bathtub alph, beta theta
*$clpstsdist[]=100000,100000, //late collapse
*$clpstfdist[]=100000,100000, //
*$startoxloss[]=10000,10000,// ox loss
*$endoxloss[]=35000,35000,
*$fpltsdist[]=10000,20000,  //start of fission product loss
*$fpltfdist[]=40000,50000,  //all fission products lost
```

Case 6

```
*VA MOX, cl=.92, delayed collapse and oxide loss


*$randflag=1 //randomize using the clock

$oxlossflag=1 //oxloss  case

*$oxlosscv=.7  //coefficient of variance for oxide loss

$pnobt=0.5225   //probability of no bathtub

$cl=0.92

$rlztns=30000    //extra iterations
*$flowdist[]=.05,.05, //current drip rate
*$btimedist[]=2.347,4.810,10.820,    //EDA breach time alph, beta, theta
*$bdurdist[]=11.881,10.218,0,    //EDA duration of bathtub alph, beta theta
$clpstsdist[]=100000,100000, //late collapse
$clpstfdist[]=100000,100000, //
*$startoxloss[]=10000,10000,// ox loss
*$endoxloss[]=35000,35000,
*$fpltsdist[]=10000,20000,  //start of fission product loss
*$fpltfdist[]=40000,50000,  //all fission products lost
```

Case 7

```
*VA MOX, cl=.92, nominal collapse and early oxide loss
*$randflag=1 //randomize using the clock
$oxlossflag=1 //oxloss  case
*$oxlosscv=.7  //coefficient of variance for oxide loss
$pnobt=0.5225   //probability of no bathtub
$cl=0.92
$rlztns=30000    //extra iterations
*$flowdist[]=.05,.05, //current drip rate
*$btimedist[]=2.347,4.810,10.820,    //EDA breach time alph, beta, theta
*$bdurdist[]=11.881,10.218,0,    //EDA duration of bathtub alph, beta theta
*$clpstsdist[]=100000,100000, //late collapse
*$clpstfdist[]=100000,100000, //
$startoxloss[]=10000,10000,// early oxide loss
$endoxloss[]=35000,35000,
*$fpltsdist[]=10000,20000,  //start of fission product loss
*$fpltfdist[]=40000,50000,  //all fission products lost
```

Case 8

```
*VA MOX, cl=.92, late collapse and early oxide loss
*$randflag=1 //randomize using the clock
$oxlossflag=1 //oxloss  case
*$oxlosscv=.7  //coefficient of variance for oxide loss
$pnobt=0.5225   //probability of no bathtub
$cl=0.92
$rlztns=30000    //extra iterations
*$flowdist[]=.05,.05, //current drip rate
*$btimedist[]=2.347,4.810,10.820,    //EDA breach time alph, beta, theta
*$bdurdist[]=11.881,10.218,0,    //EDA duration of bathtub alph, beta theta
$clpstsdist[]=100000,100000, //late collapse
$clpstfdist[]=100000,100000, //
$startoxloss[]=10000,10000,// early oxide loss
```

```
$endoxloss[]=35000,35000,
*$fpltsdist[]=10000,20000,  //start of fission product loss
*$fpltfdist[]=40000,50000,  //all fission products lost
```

Case 9

```
*VA MOX, cl=.92, nominal fpl and collapse with fplcv=.7
*$randflag=1  //randomize using the clock
*$oxlossflag=1 //oxloss  case
*$oxlosscv=.7  //coefficient of variance for oxide loss
$fplcv=.7
$pnobt=0.5225   //probability of no bathtub
$cl=0.92
$rlztns=30000    //extra iterations
*$flowdist[]=.05,.05, //current drip rate
*$btimedist[]=2.347,4.810,10.820,    //EDA breach time alph, beta, theta
*$bdurdist[]=11.881,10.218,0,     //EDA duration of bathtub alph, beta theta
*$clpstsdist[]=100000,100000, //late collapse
*$clpstfdist[]=100000,100000, //
*$startoxloss[]=10000,10000,// early oxide loss
*$endoxloss[]=35000,35000,
*$fpltsdist[]=10000,20000,  //start of fission product loss
*$fpltfdist[]=40000,50000,  //all fission products lost
```

Case 10

```
*VA MOX, cl=.92, nominal fpl and no collapse with fplcv=.7
*$randflag=1  //randomize using the clock
*$oxlossflag=1 //oxloss  case
*$oxlosscv=.7  //coefficient of variance for oxide loss
$fplcv=.7
$pnobt=0.5225   //probability of no bathtub
$cl=0.92
$rlztns=30000    //extra iterations
*$flowdist[]=.05,.05, //current drip rate
*$btimedist[]=2.347,4.810,10.820,    //EDA breach time alph, beta, theta
*$bdurdist[]=11.881,10.218,0,     //EDA duration of bathtub alph, beta theta
$clpstsdist[]=100000,100000, //late collapse
$clpstfdist[]=100000,100000, //
*$startoxloss[]=10000,10000,// early oxide loss
*$endoxloss[]=35000,35000,
*$fpltsdist[]=10000,20000,  //start of fission product loss
*$fpltfdist[]=40000,50000,  //all fission products lost
```

Case 11

```
*VA MOX, cl=.92, nominal oxloss and collapse with oxlosscv=.7
*$randflag=1  //randomize using the clock
$oxlossflag=1 //oxloss  case
$oxlosscv=.7  //coefficient of variance for oxide loss
*$fplcv=.7
$pnobt=0.5225   //probability of no bathtub
$cl=0.92
$rlztns=30000    //extra iterations
*$flowdist[]=.05,.05, //current drip rate
*$btimedist[]=2.347,4.810,10.820,    //EDA breach time alph, beta, theta
*$bdurdist[]=11.881,10.218,0,     //EDA duration of bathtub alph, beta theta
*$clpstsdist[]=100000,100000, //late collapse
```

```
*$clpstfdist[]=100000,100000, //
*$startoxloss[]=10000,10000,// early oxide loss
*$endoxloss[]=35000,35000,
*$fpltsdist[]=10000,20000,  //start of fission product loss
*$fpltfdist[]=40000,50000,  //all fission products lost
```

Case 12

```
*VA MOX, cl=.92, nominal oxloss and no collapse with oxlosscv=.7
*$randflag=1  //randomize using the clock
$oxlossflag=1 //oxloss  case
$oxlosscv=.7  //coefficient of variance for oxide loss
*$fplcv=.7
$pnobt=0.5225   //probability of no bathtub
$cl=0.92
$rlztns=30000    //extra iterations
*$flowdist[]=.05,.05, //current drip rate
*$btimedist[]=2.347,4.810,10.820,    //EDA breach time alph, beta, theta
*$bdurdist[]=11.881,10.218,0,    //EDA duration of bathtub alph, beta theta
$clpstsdist[]=100000,100000, //late collapse
$clpstfdist[]=100000,100000, //
*$startoxloss[]=10000,10000,// early oxide loss
*$endoxloss[]=35000,35000,
*$fpltsdist[]=10000,20000,  //start of fission product loss
*$fpltfdist[]=40000,50000,  //all fission products lost
```

Attachment IV. Output Files

Case 1
Relevant part of log file (junk.out), which shows those cases with $k_{eff} > 0.90$. The nominal output file, montecarlo.out shows no criticalities for this case.
time=51076 pitch=1.222 fpls=61 keff=0.9027 ifp=3
time=75468 pitch=1.233 fpls=97 keff=0.9013 ifp=4
time=80754 pitch=1.260 fpls=100 keff=0.9093 ifp=4
time=78954 pitch=1.260 fpls=75 keff=0.9076 ifp=3
time=56275 pitch=1.234 fpls=60 keff=0.9028 ifp=3
time=73819 pitch=1.254 fpls=100 keff=0.9125 ifp=4

Case 2
```
The time is Sat Aug 21 21:37:08 1999
       Kyear   Crit pkgs

           1   0.0000000
           2   0.0000000
           3   0.0000000
           4   0.0000000
           5   0.0000000
           6   0.0000000
           7   0.0000000
           8   0.0000000
           9   0.0000000
          10   0.0000000
          11   0.0000000
          12   0.0000000
          13   0.0000000
          14   0.0000000
          15   0.0000000
          16   0.0000000
          17   0.0000000
          18   0.0000000
          19   0.0000000
          20   0.0000000
          21   0.0000000
          22   0.0000000
          23   0.0000000
          24   0.0000000
          25   0.0000000
          26   0.0000000
          27   0.0000000
          28   0.0000000
          29   0.0000000
          30   0.0000000
          31   0.0000000
          32   0.0000000
          33   0.0000000
          34   0.0000000
          35   0.0000000
          36   0.0000000
          37   0.0000000
          38   0.0000000
```

```
39    0.0000000
40    0.0000000
41    0.0004798
42    0.0004798
43    0.0009595
44    0.0009595
45    0.0009595
46    0.0020390
47    0.0025187
48    0.0025187
49    0.0039580
50    0.0053972
51    0.0065966
52    0.0075561
53    0.0081558
54    0.0089954
55    0.0104346
56    0.0105546
57    0.0111543
58    0.0118739
59    0.0124736
60    0.0135530
61    0.0146325
62    0.0155920
63    0.0157119
64    0.0157119
65    0.0157119
66    0.0157119
67    0.0157119
68    0.0157119
69    0.0157119
70    0.0157119
71    0.0157119
72    0.0157119
73    0.0157119
74    0.0157119
75    0.0157119
76    0.0157119
77    0.0157119
78    0.0157119
79    0.0157119
80    0.0157119
81    0.0157119
82    0.0157119
83    0.0157119
84    0.0157119
85    0.0157119
86    0.0157119
87    0.0157119
88    0.0157119
89    0.0157119
90    0.0157119
91    0.0157119
92    0.0157119
93    0.0157119
94    0.0157119
```

```
        95    0.0157119
        96    0.0157119
        97    0.0157119
        98    0.0157119
        99    0.0157119
*VA MOX, cl=.92, nominal fpl,no collapse
numcrits@10kyr=0 exp10=0.000000 exp100=0.015712
```

Case 3

```
The time is Sat Aug 21 21:59:59 1999

     Kyear    Crit pkgs

         1    0.0000000

         2    0.0000000
         3    0.0000000
         4    0.0000000
         5    0.0000000
         6    0.0000000
         7    0.0000000
         8    0.0000000
         9    0.0000000
        10    0.0000000
        11    0.0000000
        12    0.0000000
        13    0.0000000
        14    0.0000000
        15    0.0000000
        16    0.0000000
        17    0.0000000
        18    0.0000000
        19    0.0000000
        20    0.0000000
        21    0.0000000
        22    0.0000000
        23    0.0000000
        24    0.0000000
        25    0.0000000
        26    0.0000000
        27    0.0000000
        28    0.0000000
        29    0.0000000
        30    0.0004798
        31    0.0004798
        32    0.0004798
        33    0.0009595
        34    0.0009595
        35    0.0014393
        36    0.0015592
        37    0.0025187
        38    0.0025187
        39    0.0034782
        40    0.0035982
        41    0.0035982
        42    0.0035982
        43    0.0040779
```

44	0.0050374
45	0.0051574
46	0.0051574
47	0.0051574
48	0.0052773
49	0.0057570
50	0.0057570
51	0.0058770
52	0.0058770
53	0.0058770
54	0.0059969
55	0.0059969
56	0.0059969
57	0.0065966
58	0.0065966
59	0.0065966
60	0.0065966
61	0.0065966
62	0.0065966
63	0.0065966
64	0.0065966
65	0.0065966
66	0.0065966
67	0.0065966
68	0.0065966
69	0.0065966
70	0.0065966
71	0.0065966
72	0.0065966
73	0.0065966
74	0.0065966
75	0.0065966
76	0.0065966
77	0.0065966
78	0.0065966
79	0.0065966
80	0.0065966
81	0.0065966
82	0.0065966
83	0.0065966
84	0.0065966
85	0.0065966
86	0.0065966
87	0.0065966
88	0.0065966
89	0.0065966
90	0.0065966
91	0.0065966
92	0.0065966
93	0.0065966
94	0.0065966
95	0.0065966
96	0.0065966
97	0.0065966
98	0.0065966
99	0.0065966

*VA MOX, cl=.92, early fpl,nominal collapse

```
numcrits@10kyr=0 exp10=0.000000 exp100=0.006597
```

Case 4

```
The time is Sat Aug 21 22:09:34 1999

        Kyear   Crit pkgs

            1   0.0000000

            2   0.0000000

            3   0.0000000

            4   0.0000000

            5   0.0000000
            6   0.0000000
            7   0.0000000
            8   0.0000000
            9   0.0000000
           10   0.0000000
           11   0.0000000
           12   0.0000000
           13   0.0000000
           14   0.0000000
           15   0.0000000
           16   0.0000000
           17   0.0000000
           18   0.0000000
           19   0.0000000
           20   0.0000000
           21   0.0000000
           22   0.0000000
           23   0.0000000
           24   0.0000000
           25   0.0000000
           26   0.0000000
           27   0.0004798
           28   0.0010794
           29   0.0020390
           30   0.0029985
           31   0.0037181
           32   0.0038380
           33   0.0058770
           34   0.0074362
           35   0.0081558
           36   0.0112742
           37   0.0139129
           38   0.0155920
           39   0.0178708
           40   0.0213490
           41   0.0221886
           42   0.0241076
           43   0.0298647
           44   0.0320236
           45   0.0349021
           46   0.0381404
```

```
47   0.0405392
48   0.0434177
49   0.0490548
50   0.0508539
51   0.0528928
52   0.0540922
53   0.0578103
54   0.0609287
55   0.0647667
56   0.0687247
57   0.0707637
58   0.0726827
59   0.0742419
60   0.0759210
61   0.0774802
62   0.0785597
63   0.0793992
64   0.0796391
65   0.0797590
66   0.0799989
67   0.0803587
68   0.0803587
69   0.0803587
70   0.0803587
71   0.0803587
72   0.0803587
73   0.0803587
74   0.0803587
75   0.0803587
76   0.0803587
77   0.0803587
78   0.0803587
79   0.0803587
80   0.0803587
81   0.0803587
82   0.0803587
83   0.0803587
84   0.0803587
85   0.0803587
86   0.0803587
87   0.0803587
88   0.0803587
89   0.0803587
90   0.0803587
91   0.0803587
92   0.0803587
93   0.0803587
94   0.0803587
95   0.0803587
96   0.0803587
97   0.0803587
98   0.0803587
99   0.0803587
*VA MOX, cl=.92, early fpl,no collapse
numcrits@10kyr=0 exp10=0.000000 exp100=0.080359
```

Case 4

```
The time is Sat Aug 21 22:09:34 1999

      Kyear   Crit pkgs

          1   0.0000000

          2   0.0000000

          3   0.0000000

          4   0.0000000

          5   0.0000000

          6   0.0000000

          7   0.0000000

          8   0.0000000
          9   0.0000000
         10   0.0000000
         11   0.0000000
         12   0.0000000
         13   0.0000000
         14   0.0000000
         15   0.0000000
         16   0.0000000
         17   0.0000000
         18   0.0000000
         19   0.0000000
         20   0.0000000
         21   0.0000000
         22   0.0000000
         23   0.0000000
         24   0.0000000
         25   0.0000000
         26   0.0000000
         27   0.0004798
         28   0.0010794
         29   0.0020390
         30   0.0029985
         31   0.0037181
         32   0.0038380
         33   0.0058770
         34   0.0074362
         35   0.0081558
         36   0.0112742
         37   0.0139129
         38   0.0155920
         39   0.0178708
         40   0.0213490
         41   0.0221886
         42   0.0241076
         43   0.0298647
         44   0.0320236
         45   0.0349021
         46   0.0381404
```

```
47   0.0405392
48   0.0434177
49   0.0490548
50   0.0508539
51   0.0528928
52   0.0540922
53   0.0578103
54   0.0609287
55   0.0647667
56   0.0687247
57   0.0707637
58   0.0726827
59   0.0742419
60   0.0759210
61   0.0774802
62   0.0785597
63   0.0793992
64   0.0796391
65   0.0797590
66   0.0799989
67   0.0803587
68   0.0803587
69   0.0803587
70   0.0803587
71   0.0803587
72   0.0803587
73   0.0803587
74   0.0803587
75   0.0803587
76   0.0803587
77   0.0803587
78   0.0803587
79   0.0803587
80   0.0803587
81   0.0803587
82   0.0803587
83   0.0803587
84   0.0803587
85   0.0803587
86   0.0803587
87   0.0803587
88   0.0803587
89   0.0803587
90   0.0803587
91   0.0803587
92   0.0803587
93   0.0803587
94   0.0803587
95   0.0803587
96   0.0803587
97   0.0803587
98   0.0803587
99   0.0803587
*VA MOX, cl=.92, early fpl,no collapse
numcrits@10kyr=0 exp10=0.000000 exp100=0.080359
```

Case 5

No output listed because there were no criticalities, or even any realizations with k_{eff}>0.90.

Case 6

```
The time is Sat Aug 21 22:35:27 1999

      Kyear   Crit pkgs

          1   0.0000000

          2   0.0000000

          3   0.0000000

          4   0.0000000

          5   0.0000000

          6   0.0000000

          7   0.0000000
          8   0.0000000
          9   0.0000000
         10   0.0000000
         11   0.0000000
         12   0.0000000
         13   0.0000000
         14   0.0000000
         15   0.0000000
         16   0.0000000
         17   0.0000000
         18   0.0000000
         19   0.0000000
         20   0.0000000
         21   0.0000000
         22   0.0000000
         23   0.0000000
         24   0.0000000
         25   0.0000000
         26   0.0000000
         27   0.0000000
         28   0.0000000
         29   0.0000000
         30   0.0000000
         31   0.0000000
         32   0.0000000
         33   0.0000000
         34   0.0000000
         35   0.0000000
         36   0.0000000
         37   0.0000000
         38   0.0000000
         39   0.0000000
         40   0.0000000
         41   0.0000000
         42   0.0000000
         43   0.0000000
         44   0.0000000
```

```
45   0.0000000
46   0.0000000
47   0.0000000
48   0.0000000
49   0.0000000
50   0.0000000
51   0.0000000
52   0.0000000
53   0.0004798
54   0.0004798
55   0.0004798
56   0.0014393
57   0.0019190
58   0.0019190
59   0.0019190
60   0.0019190
61   0.0019190
62   0.0019190
63   0.0019190
64   0.0019190
65   0.0019190
66   0.0019190
67   0.0019190
68   0.0019190
69   0.0019190
70   0.0019190
71   0.0019190
72   0.0019190
73   0.0019190
74   0.0019190
75   0.0019190
76   0.0019190
77   0.0019190
78   0.0019190
79   0.0019190
80   0.0019190
81   0.0019190
82   0.0019190
83   0.0019190
84   0.0019190
85   0.0019190
86   0.0019190
87   0.0019190
88   0.0019190
89   0.0019190
90   0.0019190
91   0.0019190
92   0.0019190
93   0.0019190
94   0.0019190
95   0.0019190
96   0.0019190
97   0.0019190
98   0.0019190
99   0.0019190
*VA MOX, cl=.92, delayed collapse and oxide loss
numcrits@10kyr=0 exp10=0.000000 exp100=0.001919
```

Case 7

```
The time is Sat Aug 21 22:42:51 1999

      Kyear    Crit pkgs
          1    0.0000000
          2    0.0000000
          3    0.0000000
          4    0.0000000

          5    0.0000000
          6    0.0000000
          7    0.0000000
          8    0.0000000
          9    0.0000000
         10    0.0000000
         11    0.0000000
         12    0.0000000
         13    0.0000000
         14    0.0000000
         15    0.0000000
         16    0.0000000
         17    0.0000000
         18    0.0000000
         19    0.0000000
         20    0.0000000
         21    0.0000000
         22    0.0000000
         23    0.0000000
         24    0.0000000
         25    0.0004798
         26    0.0009595
         27    0.0009595
         28    0.0009595
         29    0.0014393
         30    0.0014393
         31    0.0019190
         32    0.0019190
         33    0.0028785
         34    0.0043178
         35    0.0043178
         36    0.0043178
         37    0.0043178
         38    0.0043178
         39    0.0043178
         40    0.0049175
         41    0.0053972
         42    0.0063567
         43    0.0063567
         44    0.0068365
         45    0.0073162
         46    0.0073162
         47    0.0073162
         48    0.0073162
         49    0.0077960
         50    0.0077960
         51    0.0077960
```

```
      52   0.0077960
      53   0.0077960
      54   0.0077960
      55   0.0077960
      56   0.0077960
      57   0.0077960
      58   0.0077960
      59   0.0077960
      60   0.0077960
      61   0.0077960
      62   0.0077960
      63   0.0077960
      64   0.0077960
      65   0.0077960
      66   0.0077960
      67   0.0077960
      68   0.0077960
      69   0.0077960
      70   0.0077960
      71   0.0077960
      72   0.0077960
      73   0.0077960
      74   0.0077960
      75   0.0077960
      76   0.0077960
      77   0.0077960
      78   0.0077960
      79   0.0077960
      80   0.0077960
      81   0.0077960
      82   0.0077960
      83   0.0077960
      84   0.0077960
      85   0.0077960
      86   0.0077960
      87   0.0077960
      88   0.0077960
      89   0.0077960
      90   0.0077960
      91   0.0077960
      92   0.0077960
      93   0.0077960
      94   0.0077960
      95   0.0077960
      96   0.0077960
      97   0.0077960
      98   0.0077960
      99   0.0077960
*VA MOX, cl=.92, nominal collapse and early oxide loss
numcrits@10kyr=0 exp10=0.000000 exp100=0.007796
```

Case 8

```
The time is Sat Aug 21 22:48:12 1999

       Kyear   Crit pkgs
```

1	0.0000000
2	0.0000000
3	0.0000000
4	0.0000000
5	0.0000000
6	0.0000000
7	0.0000000
8	0.0000000
9	0.0000000
10	0.0000000
11	0.0000000
12	0.0000000
13	0.0000000
14	0.0000000
15	0.0000000
16	0.0000000
17	0.0000000
18	0.0000000
19	0.0000000
20	0.0000000
21	0.0000000
22	0.0000000
23	0.0000000
24	0.0009595
25	0.0009595
26	0.0009595
27	0.0015592
28	0.0016791
29	0.0026386
30	0.0038380
31	0.0047975
32	0.0055172
33	0.0070764
34	0.0087555
35	0.0105546
36	0.0122337
37	0.0137929
38	0.0153521
39	0.0169113
40	0.0183506
41	0.0201497
42	0.0235079
43	0.0265064
44	0.0289052
45	0.0313039
46	0.0341824
47	0.0361015
48	0.0399395
49	0.0408990
50	0.0437775
51	0.0461763
52	0.0485751
53	0.0519333
54	0.0552916
55	0.0572106

```
          56   0.0581701
          57   0.0605689
          58   0.0615284
          59   0.0639272
          60   0.0653664
          61   0.0653664
          62   0.0653664
          63   0.0653664
          64   0.0653664
          65   0.0653664
          66   0.0653664
          67   0.0653664
          68   0.0653664
          69   0.0653664
          70   0.0653664
          71   0.0653664
          72   0.0653664
          73   0.0653664
          74   0.0653664
          75   0.0653664
          76   0.0653664
          77   0.0653664
          78   0.0653664
          79   0.0653664
          80   0.0653664
          81   0.0653664
          82   0.0653664
          83   0.0653664
          84   0.0653664
          85   0.0653664
          86   0.0653664
          87   0.0653664
          88   0.0653664
          89   0.0653664
          90   0.0653664
          91   0.0653664
          92   0.0653664
          93   0.0653664
          94   0.0653664
          95   0.0653664
          96   0.0653664
          97   0.0653664
          98   0.0653664
          99   0.0653664
*VA MOX, cl=.92, late collapse and early oxide loss
numcrits@10kyr=0 exp10=0.000000 exp100=0.065366
```

Case 9
*VA MOX, cl=.92, nominal fpl and collapse with fplcv=.7
numcrits@10kyr=0 exp10=0.000000 exp100=0.000000
time=43947 pitch=1.183 fpls=75 keff=0.9048 ifp=4
time=49947 pitch=1.196 fpls=67 keff=0.9005 ifp=3
time=59098 pitch=1.237 fpls=63 keff=0.9066 ifp=3
time=55344 pitch=1.210 fpls=73 keff=0.9050 ifp=3
time=46059 pitch=1.219 fpls=51 keff=0.9020 ifp=3

time=31890 pitch=1.198 fpls=61 keff=0.9033 ifp=3
time=46890 pitch=1.183 fpls=100 keff=0.9050 ifp=4
time=72356 pitch=1.230 fpls=85 keff=0.9001 ifp=4
time=33972 pitch=1.214 fpls=61 keff=0.9086 ifp=3
time=45972 pitch=1.178 fpls=76 keff=0.9017 ifp=4
time=43565 pitch=1.209 fpls=61 keff=0.9058 ifp=3
time=47565 pitch=1.181 fpls=73 keff=0.9002 ifp=3
time=56782 pitch=1.221 fpls=84 keff=0.9095 ifp=4
time=41790 pitch=1.187 fpls=67 keff=0.9014 ifp=3
time=54790 pitch=1.226 fpls=98 keff=0.9136 ifp=4
time=56571 pitch=1.210 fpls=72 keff=0.9036 ifp=3
time=55649 pitch=1.214 fpls=72 keff=0.9058 ifp=3
time=65932 pitch=1.227 fpls=71 keff=0.9018 ifp=3
time=57654 pitch=1.260 fpls=69 keff=0.9190 ifp=3
time=57462 pitch=1.220 fpls=68 keff=0.9017 ifp=3
time=49550 pitch=1.212 fpls=71 keff=0.9061 ifp=3
time=53550 pitch=1.196 fpls=87 keff=0.9027 ifp=4
time=37186 pitch=1.213 fpls=68 keff=0.9093 ifp=3
time=38186 pitch=1.201 fpls=69 keff=0.9059 ifp=3
time=44186 pitch=1.181 fpls=75 keff=0.9005 ifp=3
time=45186 pitch=1.192 fpls=79 keff=0.9056 ifp=4
time=87405 pitch=1.260 fpls=84 keff=0.9026 ifp=4
time=54282 pitch=1.197 fpls=83 keff=0.9012 ifp=4
time=52006 pitch=1.205 fpls=78 keff=0.9050 ifp=4
time=51830 pitch=1.214 fpls=65 keff=0.9014 ifp=3
time=48243 pitch=1.188 fpls=100 keff=0.9070 ifp=4
time=50198 pitch=1.210 fpls=67 keff=0.9022 ifp=3
time=32432 pitch=1.239 fpls=64 keff=0.9162 ifp=3
time=38432 pitch=1.227 fpls=56 keff=0.9053 ifp=3
time=48539 pitch=1.205 fpls=100 keff=0.9136 ifp=4
time=54741 pitch=1.252 fpls=47 keff=0.9011 ifp=2

Case 10

```
The time is Sun Aug 22 08:44:26 1999

        Kyear   Crit pkgs

             1   0.0000000

             2   0.0000000

             3   0.0000000

             4   0.0000000

             5   0.0000000

             6   0.0000000
             7   0.0000000
             8   0.0000000
```

```
 9   0.0000000
10   0.0000000
11   0.0000000
12   0.0000000
13   0.0000000
14   0.0000000
15   0.0000000
16   0.0000000
17   0.0000000
18   0.0000000
19   0.0000000
20   0.0000000
21   0.0000000
22   0.0000000
23   0.0000000
24   0.0000000
25   0.0000000
26   0.0000000
27   0.0000000
28   0.0000000
29   0.0000000
30   0.0000000
31   0.0000000
32   0.0004798
33   0.0014393
34   0.0019190
35   0.0019190
36   0.0025187
37   0.0025187
38   0.0035982
39   0.0040779
40   0.0045577
41   0.0056371
42   0.0056371
43   0.0071963
44   0.0082758
45   0.0098349
46   0.0107945
47   0.0146325
48   0.0171512
49   0.0184705
50   0.0197898
51   0.0220687
52   0.0249472
53   0.0267463
54   0.0278257
55   0.0293849
56   0.0309441
57   0.0347821
58   0.0356217
59   0.0375407
60   0.0401794
61   0.0413788
62   0.0419784
63   0.0423383
64   0.0423383
65   0.0424582
```

```
       66    0.0429380
       67    0.0431778
       68    0.0431778
       69    0.0431778
       70    0.0431778
       71    0.0431778
       72    0.0431778
       73    0.0431778
       74    0.0431778
       75    0.0431778
       76    0.0431778
       77    0.0431778
       78    0.0431778
       79    0.0431778
       80    0.0431778
       81    0.0431778
       82    0.0431778
       83    0.0431778
       84    0.0431778
       85    0.0431778
       86    0.0431778
       87    0.0431778
       88    0.0431778
       89    0.0431778
       90    0.0431778
       91    0.0431778
       92    0.0431778
       93    0.0431778
       94    0.0431778
       95    0.0431778
       96    0.0431778
       97    0.0431778
       98    0.0431778
       99    0.0431778
*VA MOX, cl=.92, nominal fpl and no collapse with fplcv=.7
numcrits@10kyr=0 exp10=0.000000 exp100=0.043178
```

Case 12

```
The time is Sun Aug 22 09:03:23 1999
    Kyear    Crit pkgs
        1    0.0000000
        2    0.0000000
        3    0.0000000
        4    0.0000000
        5    0.0000000
        6    0.0000000
        7    0.0000000
        8    0.0000000
        9    0.0000000
       10    0.0000000
       11    0.0000000
       12    0.0000000
       13    0.0000000
       14    0.0000000
       15    0.0000000
       16    0.0000000
       17    0.0000000
```

```
18     0.0000000
19     0.0000000
20     0.0000000
21     0.0000000
22     0.0000000
23     0.0000000
24     0.0000000
25     0.0000000
26     0.0000000
27     0.0000000
28     0.0000000
29     0.0000000
30     0.0000000
31     0.0000000
32     0.0000000
33     0.0000000
34     0.0000000
35     0.0000000
36     0.0000000
37     0.0000000
38     0.0000000
39     0.0000000
40     0.0004798
41     0.0009595
42     0.0009595
43     0.0009595
44     0.0019190
45     0.0019190
46     0.0023988
47     0.0023988
48     0.0028785
49     0.0033583
50     0.0038380
51     0.0047975
52     0.0052773
53     0.0057570
54     0.0062368
55     0.0086356
56     0.0110343
57     0.0119938
58     0.0129533
59     0.0129533
60     0.0134331
61     0.0134331
62     0.0134331
63     0.0134331
64     0.0134331
65     0.0134331
66     0.0134331
67     0.0134331
68     0.0134331
69     0.0134331
70     0.0134331
71     0.0134331
72     0.0134331
73     0.0134331
74     0.0134331
```

```
          75    0.0134331
          76    0.0134331
          77    0.0134331
          78    0.0134331
          79    0.0134331
          80    0.0134331
          81    0.0134331
          82    0.0134331
          83    0.0134331
          84    0.0134331
          85    0.0134331
          86    0.0134331
          87    0.0134331
          88    0.0134331
          89    0.0134331
          90    0.0134331
          91    0.0134331
          92    0.0134331
          93    0.0134331
          94    0.0134331
          95    0.0134331
          96    0.0134331
          97    0.0134331
          98    0.0134331
          99    0.0134331
*VA MOX, cl=.92, nominal oxloss and no collapse with oxlosscv=.7
numcrits@10kyr=0 exp10=0.000000 exp100=0.013433
```

Attachment V. Criticality Lookup Tables

The values of k_{eff} for varying the degradation parameters of assembly pitch and fission product loss are given in Table V-1. The k_{eff} is also sensitive to initial enrichment and time since discharge (assumed to be the same as time since emplacement, Assumption 3.6), so these parameters also vary in the table. The data in this table is taken from Reference 9, Tables 6-1 through 6-10.

Table V-1. Values of k_{eff} for Varying Assembly Pitch and Fission Product Loss

k_{eff}	Initial wt% Pu	Pitch (cm)	Time (years)	Fission Product Loss (%)
0.71093	4.00	0.91440	10000.0	0.0
0.72484	4.00	0.91440	10000.0	25.0
0.74631	4.00	0.91440	10000.0	50.0
0.76518	4.00	0.91440	10000.0	75.0
0.78893	4.00	0.91440	10000.0	100.0
0.72547	4.00	0.91440	25000.0	0.0
0.74631	4.00	0.91440	25000.0	25.0
0.76777	4.00	0.91440	25000.0	50.0
0.79567	4.00	0.91440	25000.0	75.0
0.82162	4.00	0.91440	25000.0	100.0
0.72511	4.00	0.91440	45000.0	0.0
0.74918	4.00	0.91440	45000.0	25.0
0.77495	4.00	0.91440	45000.0	50.0
0.80146	4.00	0.91440	45000.0	75.0
0.83403	4.00	0.91440	45000.0	100.0
0.69360	4.00	0.91440	100000.0	0.0
0.69302	4.00	0.91440	100000.0	25.0
0.74730	4.00	0.91440	100000.0	50.0
0.77665	4.00	0.91440	100000.0	75.0
0.81507	4.00	0.91440	100000.0	100.0
0.75244	4.00	1.00076	10000.0	0.0
0.77058	4.00	1.00076	10000.0	25.0
0.79091	4.00	1.00076	10000.0	50.0
0.81550	4.00	1.00076	10000.0	75.0
0.84204	4.00	1.00076	10000.0	100.0
0.77559	4.00	1.00076	25000.0	0.0
0.79788	4.00	1.00076	25000.0	25.0
0.81985	4.00	1.00076	25000.0	50.0
0.84708	4.00	1.00076	25000.0	75.0
0.87748	4.00	1.00076	25000.0	100.0
0.76796	4.00	1.00076	45000.0	0.0
0.79340	4.00	1.00076	45000.0	25.0
0.82122	4.00	1.00076	45000.0	50.0
0.85183	4.00	1.00076	45000.0	75.0
0.88529	4.00	1.00076	45000.0	100.0
0.72904	4.00	1.00076	100000.0	0.0
0.73079	4.00	1.00076	100000.0	25.0
0.78670	4.00	1.00076	100000.0	50.0
0.81809	4.00	1.00076	100000.0	75.0
0.85660	4.00	1.00076	100000.0	100.0
0.79430	4.00	1.08712	10000.0	0.0
0.81232	4.00	1.08712	10000.0	25.0
0.83460	4.00	1.08712	10000.0	50.0
0.85590	4.00	1.08712	10000.0	75.0
0.88350	4.00	1.08712	10000.0	100.0

k_{eff}	Initial wt% Pu	Pitch (cm)	Time (years)	Fission Product Loss (%)
0.81048	4.00	1.08712	25000.0	0.0
0.83403	4.00	1.08712	25000.0	25.0
0.86054	4.00	1.08712	25000.0	50.0
0.88581	4.00	1.08712	25000.0	75.0
0.91862	4.00	1.08712	25000.0	100.0
0.79948	4.00	1.08712	45000.0	0.0
0.82622	4.00	1.08712	45000.0	25.0
0.85599	4.00	1.08712	45000.0	50.0
0.88447	4.00	1.08712	45000.0	75.0
0.91738	4.00	1.08712	45000.0	100.0
0.75335	4.00	1.08712	100000.0	0.0
0.75422	4.00	1.08712	100000.0	25.0
0.81195	4.00	1.08712	100000.0	50.0
0.84380	4.00	1.08712	100000.0	75.0
0.87957	4.00	1.08712	100000.0	100.0
0.82454	4.00	1.17348	10000.0	0.0
0.84092	4.00	1.17348	10000.0	25.0
0.86199	4.00	1.17348	10000.0	50.0
0.88537	4.00	1.17348	10000.0	75.0
0.91032	4.00	1.17348	10000.0	100.0
0.83435	4.00	1.17348	25000.0	0.0
0.85955	4.00	1.17348	25000.0	25.0
0.88176	4.00	1.17348	25000.0	50.0
0.90956	4.00	1.17348	25000.0	75.0
0.93708	4.00	1.17348	25000.0	100.0
0.81886	4.00	1.17348	45000.0	0.0
0.84284	4.00	1.17348	45000.0	25.0
0.87086	4.00	1.17348	45000.0	50.0
0.90064	4.00	1.17348	45000.0	75.0
0.93458	4.00	1.17348	45000.0	100.0
0.76691	4.00	1.17348	100000.0	0.0
0.76686	4.00	1.17348	100000.0	25.0
0.82553	4.00	1.17348	100000.0	50.0
0.85403	4.00	1.17348	100000.0	75.0
0.88927	4.00	1.17348	100000.0	100.0
0.83855	4.00	1.25984	10000.0	0.0
0.85792	4.00	1.25984	10000.0	25.0
0.87967	4.00	1.25984	10000.0	50.0
0.90477	4.00	1.25984	10000.0	75.0
0.92546	4.00	1.25984	10000.0	100.0
0.84689	4.00	1.25984	25000.0	0.0
0.86969	4.00	1.25984	25000.0	25.0
0.89478	4.00	1.25984	25000.0	50.0
0.92102	4.00	1.25984	25000.0	75.0
0.94725	4.00	1.25984	25000.0	100.0
0.82322	4.00	1.25984	45000.0	0.0
0.85307	4.00	1.25984	45000.0	25.0
0.87607	4.00	1.25984	45000.0	50.0
0.90313	4.00	1.25984	45000.0	75.0
0.93413	4.00	1.25984	45000.0	100.0
0.77119	4.00	1.25984	100000.0	0.0
0.76972	4.00	1.25984	100000.0	25.0
0.82493	4.00	1.25984	100000.0	50.0
0.85406	4.00	1.25984	100000.0	75.0
0.88775	4.00	1.25984	100000.0	100.0
0.69801	4.50	0.91440	10000.0	0.0
0.71664	4.50	0.91440	10000.0	25.0

k_{eff}	Initial wt% Pu	Pitch (cm)	Time (years)	Fission Product Loss (%)
0.73673	4.50	0.91440	10000.0	50.0
0.75894	4.50	0.91440	10000.0	75.0
0.78558	4.50	0.91440	10000.0	100.0
0.71780	4.50	0.91440	25000.0	0.0
0.73943	4.50	0.91440	25000.0	25.0
0.76116	4.50	0.91440	25000.0	50.0
0.78999	4.50	0.91440	25000.0	75.0
0.81695	4.50	0.91440	25000.0	100.0
0.71549	4.50	0.91440	45000.0	0.0
0.74075	4.50	0.91440	45000.0	25.0
0.76739	4.50	0.91440	45000.0	50.0
0.79822	4.50	0.91440	45000.0	75.0
0.83040	4.50	0.91440	45000.0	100.0
0.68286	4.50	0.91440	100000.0	0.0
0.71017	4.50	0.91440	100000.0	25.0
0.73768	4.50	0.91440	100000.0	50.0
0.77427	4.50	0.91440	100000.0	75.0
0.81237	4.50	0.91440	100000.0	100.0
0.74188	4.50	1.00076	10000.0	0.0
0.76292	4.50	1.00076	10000.0	25.0
0.78512	4.50	1.00076	10000.0	50.0
0.80901	4.50	1.00076	10000.0	75.0
0.83378	4.50	1.00076	10000.0	100.0
0.76122	4.50	1.00076	25000.0	0.0
0.78618	4.50	1.00076	25000.0	25.0
0.81140	4.50	1.00076	25000.0	50.0
0.84281	4.50	1.00076	25000.0	75.0
0.86941	4.50	1.00076	25000.0	100.0
0.75423	4.50	1.00076	45000.0	0.0
0.78322	4.50	1.00076	45000.0	25.0
0.81192	4.50	1.00076	45000.0	50.0
0.84610	4.50	1.00076	45000.0	75.0
0.88349	4.50	1.00076	45000.0	100.0
0.71589	4.50	1.00076	100000.0	0.0
0.74552	4.50	1.00076	100000.0	25.0
0.77783	4.50	1.00076	100000.0	50.0
0.81583	4.50	1.00076	100000.0	75.0
0.85371	4.50	1.00076	100000.0	100.0
0.77908	4.50	1.08712	10000.0	0.0
0.80015	4.50	1.08712	10000.0	25.0
0.82333	4.50	1.08712	10000.0	50.0
0.84910	4.50	1.08712	10000.0	75.0
0.87219	4.50	1.08712	10000.0	100.0
0.79894	4.50	1.08712	25000.0	0.0
0.82340	4.50	1.08712	25000.0	25.0
0.84952	4.50	1.08712	25000.0	50.0
0.88166	4.50	1.08712	25000.0	75.0
0.90860	4.50	1.08712	25000.0	100.0
0.78605	4.50	1.08712	45000.0	0.0
0.81538	4.50	1.08712	45000.0	25.0
0.84630	4.50	1.08712	45000.0	50.0
0.88002	4.50	1.08712	45000.0	75.0
0.91417	4.50	1.08712	45000.0	100.0
0.74212	4.50	1.08712	100000.0	0.0
0.76900	4.50	1.08712	100000.0	25.0
0.80580	4.50	1.08712	100000.0	50.0
0.84264	4.50	1.08712	100000.0	75.0

k_{eff}	Initial wt% Pu	Pitch (cm)	Time (years)	Fission Product Loss (%)
0.87986	4.50	1.08712	100000.0	100.0
0.80635	4.50	1.17348	10000.0	0.0
0.83117	4.50	1.17348	10000.0	25.0
0.85441	4.50	1.17348	10000.0	50.0
0.88039	4.50	1.17348	10000.0	75.0
0.90502	4.50	1.17348	10000.0	100.0
0.82065	4.50	1.17348	25000.0	0.0
0.84552	4.50	1.17348	25000.0	25.0
0.87761	4.50	1.17348	25000.0	50.0
0.90506	4.50	1.17348	25000.0	75.0
0.93639	4.50	1.17348	25000.0	100.0
0.80536	4.50	1.17348	45000.0	0.0
0.83539	4.50	1.17348	45000.0	25.0
0.86464	4.50	1.17348	45000.0	50.0
0.89739	4.50	1.17348	45000.0	75.0
0.93133	4.50	1.17348	45000.0	100.0
0.75435	4.50	1.17348	100000.0	0.0
0.78447	4.50	1.17348	100000.0	25.0
0.81748	4.50	1.17348	100000.0	50.0
0.85176	4.50	1.17348	100000.0	75.0
0.89320	4.50	1.17348	100000.0	100.0
0.82764	4.50	1.25984	10000.0	0.0
0.84925	4.50	1.25984	10000.0	25.0
0.87286	4.50	1.25984	10000.0	50.0
0.89758	4.50	1.25984	10000.0	75.0
0.92293	4.50	1.25984	10000.0	100.0
0.83466	4.50	1.25984	25000.0	0.0
0.86027	4.50	1.25984	25000.0	25.0
0.88643	4.50	1.25984	25000.0	50.0
0.91894	4.50	1.25984	25000.0	75.0
0.94949	4.50	1.25984	25000.0	100.0
0.81323	4.50	1.25984	45000.0	0.0
0.84098	4.50	1.25984	45000.0	25.0
0.86988	4.50	1.25984	45000.0	50.0
0.90427	4.50	1.25984	45000.0	75.0
0.93911	4.50	1.25984	45000.0	100.0
0.75896	4.50	1.25984	100000.0	0.0
0.78903	4.50	1.25984	100000.0	25.0
0.81876	4.50	1.25984	100000.0	50.0
0.85261	4.50	1.25984	100000.0	75.0
0.89318	4.50	1.25984	100000.0	100.0

The values of k_{eff} for varying the degradation parameters of assembly pitch and iron oxide loss are given in Table V-2. As with Table V-1, the k_{eff} is also sensitive to initial enrichment and time since discharge, so these parameters also vary in the table. The data in this table is taken from Reference 9, Tables 6-11 and 6-12.

Table V-2. Values of k_{eff} for Varying Assembly Pitch and Iron Oxide Loss

k_{eff}	Initial wt% Pu	Pitch (cm)	Time (years)	Iron Oxide Loss (%)
0.72547	4.00	0.91440	25000.0	0.0
0.73440	4.00	0.91440	25000.0	10.0
0.74537	4.00	0.91440	25000.0	25.0
0.76436	4.00	0.91440	25000.0	50.0
0.78441	4.00	0.91440	25000.0	75.0
0.69360	4.00	0.91440	100000.0	0.0
0.70139	4.00	0.91440	100000.0	10.0
0.71517	4.00	0.91440	100000.0	25.0
0.72881	4.00	0.91440	100000.0	50.0
0.74765	4.00	0.91440	100000.0	75.0
0.84689	4.00	1.25984	25000.0	0.0
0.86085	4.00	1.25984	25000.0	10.0
0.88371	4.00	1.25984	25000.0	25.0
0.91950	4.00	1.25984	25000.0	50.0
0.95234	4.00	1.25984	25000.0	75.0
0.77119	4.00	1.25984	100000.0	0.0
0.78719	4.00	1.25984	100000.0	10.0
0.80619	4.00	1.25984	100000.0	25.0
0.84332	4.00	1.25984	100000.0	50.0
0.88409	4.00	1.25984	100000.0	75.0
0.71780	4.50	0.91440	25000.0	0.0
0.72529	4.50	0.91440	25000.0	10.0
0.73629	4.50	0.91440	25000.0	25.0
0.74972	4.50	0.91440	25000.0	50.0
0.77257	4.50	0.91440	25000.0	75.0
0.68286	4.50	0.91440	100000.0	0.0
0.68877	4.50	0.91440	100000.0	10.0
0.69930	4.50	0.91440	100000.0	25.0
0.71312	4.50	0.91440	100000.0	50.0
0.73223	4.50	0.91440	100000.0	75.0
0.83466	4.50	1.25984	25000.0	0.0
0.84967	4.50	1.25984	25000.0	10.0
0.87010	4.50	1.25984	25000.0	25.0
0.90608	4.50	1.25984	25000.0	50.0
0.93809	4.50	1.25984	25000.0	75.0
0.75896	4.50	1.25984	100000.0	0.0
0.77254	4.50	1.25984	100000.0	10.0
0.79500	4.50	1.25984	100000.0	25.0
0.83050	4.50	1.25984	100000.0	50.0
0.86642	4.50	1.25984	100000.0	75.0